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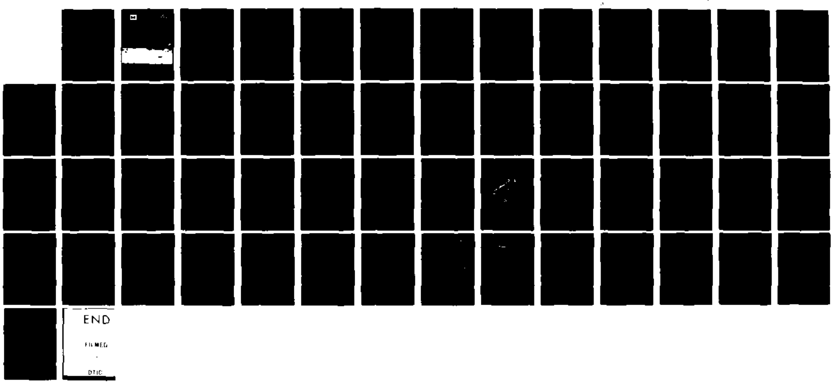

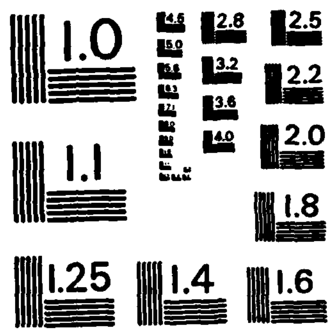

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THE USE OF DOWNHOLE GEOPHYSICAL METHODS TO DETECT ZONES OF POOR-QUALITY ROCK OR VOIDS

by

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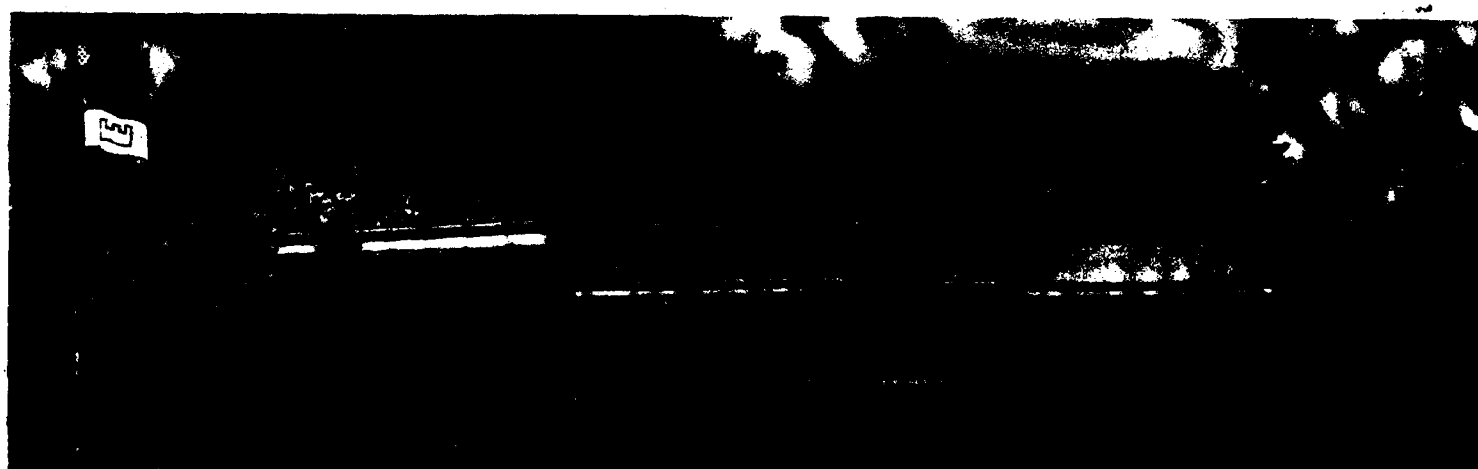
September 1982

Final Report



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This report documents the current state of the art of using downhole geophysical methods to detect zones of poor-quality rock or voids in foundation investigations extending to hundreds of metres in depth. In this situation, exploratory borings are very costly, and the use of geophysical methods could be effective in minimizing drilling costs without sacrificing the truth in formation which only borings can provide.

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20. ABSTRACT (Continued).

The primary objective of the study was to evaluate existing downhole geophysical capabilities to detect poor-quality rock or voids at depths up to hundreds of metres and at distances on the order of tens of metres from the borehole. After an extensive literature review and contacts with the geophysical community, it was determined that no single borehole device offered the desired capability. However, crosshole testing did provide some of the directionality and detection capabilities sought and this approach was considered to be the only viable and cost-effective alternative remaining.

Accordingly, a series of crosshole method field evaluations were carried out at two WES research sites in Florida. Both sites are in extensively solutioned limestone, with the Medford Cave site typifying dry (air-filled) cavities and the Manatee Springs site typifying wet (water-filled) cavities. In the course of these studies conventional single borehole logging methods were used to typify the site materials, and crosshole acoustic, electromagnetic, and resistivity methods were evaluated on known cavity features.

Results of the investigation indicate that the crosshole methods can detect known cavity features with borehole spacing on the order of 20 to 50 ft (6.1 to 15.2 m), depending on site conditions. Results of the various field evaluations, a brief summary of potentially useful methods now under development, and recommended guidelines for use of complementary conventional and crosshole methods are provided in this report.

PREFACE

This investigation was conducted by the U. S. Army Engineer Waterways Experiment Station (WES) for the Office, Chief of Engineers (OCE), U. S. Army, under Project 4A161102AT22, Task A0, Work Unit 003, entitled "Downhole Geophysical Exploration Techniques." Mr. A. F. Muller, OCE, was the Technical Monitor for the project.

The field work for this study was carried out at two test sites in Florida at various times in the period September 1979-October 1981. The test sites were developed and used as part of a joint program with funding from CWIS Work Unit 31150. Mr. Paul Fisher, OCE, was the Technical Monitor for the CWIS project. Individuals contributing to the planning, field work, and analysis phases of this study were Messrs. S. S. Cooper, J. P. Koester, D. E. Yule, and G. W. Deer of the Earthquake Engineering and Geophysics Division (EE&GD), Geotechnical Laboratory (GL), under the direct supervision of Dr. A. G. Franklin, Chief, EE&GD, GL. The work was performed under the general supervision of Dr. W. F. Marcuson III, Chief, GL. This report was prepared by Mr. Cooper.

Commanders and Directors of WES during this study were COL Nelson P. Conover, CE, and COL Tilford C. Creel, CE. Mr. Fred R. Brown was Technical Director.

CONTENTS

THE USE OF DOWNHOLE GEOPHYSICAL METHODS TO DETECT ZONES OF POOR-QUALITY ROCK OR VOIDS

PART I: INTRODUCTION

Background

1. Foundation investigations can extend to depths up to hundreds of metres for deep-hardened military facilities or other special purpose structures founded in rock. A primary concern in such investigations is to identify zones of poor quality rock or voids which could pose a significant threat to the survivability of the structure and/or require special design consideration. For this application, it is necessary both to detect the anomalous zone and to delineate its physical dimensions for input to the process of foundation design or remedial treatment. Drilling and coring are indispensable methods to confirm subsurface conditions, but extensive coverage with closely spaced deep borings greatly increases time and costs. Also, even a dense population of borings may fail to detect some features of considerable size and significance. Downhole geophysical methods are attractive in this kind of problem because their successful use could provide adequate coverage while minimizing drilling costs.

Purpose

2. This study was funded by the Office, Chief of Engineers, U. S. Army, to determine the feasibility of using downhole geophysical methods to sense poor-quality rock or voids at depths on the order of hundreds of metres. Geophysical methods which might sense anomalies located at distances on the order of tens of metres from the borehole were of primary importance in the study.

Scope

3. This report presents a review of candidate downhole geophysical methods and documents limited field testing of selected techniques at two limestone research sites in Florida. Included is a summary of downhole exploration capabilities based on the current state of the art, and recommendations are made for a balanced program of borings and geophysical surveys to suit the general requirements of a deep investigation in rock.

PART II: REVIEW OF CANDIDATE DOWNHOLE GEOPHYSICAL TECHNIQUES

4. Since the 1930's, the oil well logging industry has provided a wealth of information on borehole methods developed to detect hydrocarbon bearing strata (Schlumberger, Ltd, 1972 and 1974; American Petroleum Institute, 1959; Titman, 1956; Titman et al., 1966; Titman and Wahl, 1965; Pirson, 1963; and others) at depths on the order of thousands of metres. Conventional borehole logging methods have also been successfully applied to problems in hydrology (Keys and MacCary, 1971) and civil engineering (Guyod, 1969; Hunt 1977). Qualitative analyses of logging data are usually performed to determine stratigraphy and lithology, and to correlate structure between adjacent borings. Quantitative analyses are generally restricted to zones of interest since such analyses require considerable expertise and judgment and a number of factors, such as borehole irregularities, can adversely affect the accuracy of results.

5. A key element in this study is the requirement for geophysical methods having radii of investigation on the order of tens of metres. The question of the radius of investigation of conventional methods and possible refinements to these methods to produce the desired result is addressed in the next section.

Conventional Borehole Exploration Techniques

6. The intent of this discussion is to review only those conventional logging methods that have proven or possible application to sensing voids or poor-quality rock. For a comprehensive treatment of methods used in geophysical explorations the reader is referred to the recent literature (Headquarters, Department of the Army, 1979).

7. The most commonly recommended suite of logging methods and their principal input to engineering property determinations is as follows:

- a. Caliper (borehole irregularity).
- b. Gamma ray (lithology, natural gamma radiation).

c. Gamma-gamma (bulk density).

d. Neutron (porosity).

e. Three-dimensional (3-D) velocity (P- and S-wave velocity).

8. It is assumed that the 3-D method will either be used in rock below the water table, or that P- and S-wave velocities can be determined by other means since the 3-D velocity tool and other conventional acoustic tools require a fluid-filled borehole. Formation grain density values must also be determined from a few core samples in order to derive the dry density of the rock strata below the water table.

9. The caliper log is used to measure irregularities in borehole diameter so that appropriate compensation factors can be applied in the interpretation of the nuclear logs. The gamma ray tool provides lithologic information as well as a record of natural gamma radiation which may be used to correct the gamma-gamma data (the gamma-gamma density tool detectors record total gamma radiation, both induced and natural). The neutron tools record the total volume of water contained in the strata investigated, including any chemically bound water. Provided there is little or no chemically bound water present and accurate calibrations have been performed, the nuclear tools can measure values of bulk density and porosity which are in good agreement with core sample data. The 3-D velocity tool can provide P-wave velocity with good accuracy, but S-wave velocities are not so easily determined, and in fact, are often estimated. Conventional nuclear tools are generally considered to have a radius of investigation of about 1 ft (0.3 m). The radius of investigation of 3-D and other similar acoustic devices does not exceed 3 ft (0.9 m), and is probably typically much less than this value (Headquarters, Department of the Army, 1979).

10. In the event that a borehole does intersect a zone of poor-quality rock, other tools may be used to further define the feature. If fracturing is in evidence below the water table, then a sonic borehole imagery tool may be used to produce an image of voids in the fracture zone. Special acoustic calipers may be used to define the dimensions of large water-filled cavities penetrated by the borehole. The maximum radius of investigation into a cavity with the acoustic caliper method

is about 100 ft (30.5 m), line of sight. A borehole television camera may also be used if viewing conditions permit (in air, or when the drilling fluid is clear water).

11. Other single borehole logging methods, such as spontaneous potential (SP) and resistivity, are widely used for a variety of logging applications but have not been used specifically to sense the presence of poor-quality rock or voids outside the borehole. Such applications of the methods may be possible, but these methods depend solely on the presence of pore fluid to make the electrical measurement and do not provide a direct index of fracturing or mass deficiencies resulting from large voids. Consequently, indications of an anomalous SP or resistivity condition are inherently ambiguous unless and until other means of validation are employed. So-called focused current resistivity devices have been developed by commercial logging firms to increase the lateral radius of investigation of resistivity tools in resistive (rock) strata. The single borehole focusing concept has been hotly debated, and there is no recorded instance where a focused current device has successfully identified the presence of voids near, but not intersecting, the borehole.

12. Despite their limitations, of which the most important is a radius of investigation of no more than a few feet (approximately 1 m) in rock, conventional logging tools can provide much useful information in addition to a continuous record of subsurface strata penetrated by the borehole. This kind of information is needed to correlate with results that may be obtained using other methods. The possibility of modifying or refining existing logging equipment to sense remote features is discussed in the next section.

Possible Refinements to Existing Single Borehole Techniques

13. Since no currently available conventional borehole logging equipment provides the desired radius of investigation (tens of metres), some consideration was given to modifications which might be made to this end. For resistivity logging tools using a "normal" electrode

configuration, the radius of investigation is assumed to be the spacing between current and measurement electrodes, typically 1.33 to 5.33 ft (0.41 to 1.63 m). In principle, the depth of investigation in a formation could be extended simply by increasing the electrode spacing. Unfortunately, to achieve 50 ft (15.24 m) depth of investigation, for example, the electrode spacing would also have to be 50 ft (15.24 m) and resolution of fracture zones equal to or less than 50 ft (15.25 m) in thickness would be virtually impossible. Also, the volume of material investigated would prohibit resolution of features of a size significant to the foundation designer. The possibility of using a focused current single borehole resistivity device was discarded for reasons discussed earlier.

14. Collimated nuclear devices are widely used and are capable of directed (oriented) measurements. Unfortunately, their radius of investigation is on the order of approximately 1 ft (0.3 m), and using longer source-to-detector spacings to increase the radius of investigation would require the use of an extremely high-level radiation source which would be potentially hazardous to personnel as well as too dangerous in the event of loss in the borehole. Achieving greater depths of investigation by this means is clearly not practical.

15. Finally, consideration was given to extending the recording time of a sonic borehole imagery tool or 3-D acoustic device so as to receive signals reflected from remote features. This approach would undoubtedly require development of a much more powerful signal source than is currently available as well as development of a technique to distinguish reflections from the remote feature from other events occurring in a complex wave train. This approach, while feasible in theory, did not promise to yield immediate results and was not given further consideration for purposes of this investigation.

16. The only other approach considered to have good prospects of yielding immediate results was the use of crosshole methods to provide the radius of investigation and directionally lacking in conventional single borehole methods. This approach is the next topic of discussion.

Crosshole Techniques

17. The U. S. Army Engineer Waterways Experiment Station (WES) has had considerable experience with acoustic crosshole studies (Ballard, 1976; Butler, Skoglund, and Landers, 1978) to determine elastic properties of in situ materials. This method requires a seismic source in one borehole and a detector at the same or different elevation in an adjacent hole. While two boreholes are required rather than one, it was reasoned that this sort of approach could still offer some economies in drilling provided that the spacing between boreholes could be on the order of tens of metres, and that it should be feasible to at least detect zones of poor-quality rock or even obtain an image of such zones under favorable conditions. It was believed that the primary influence on system response would be from the shortest travel path through the media between the boreholes, rather than through surrounding strata. This is probably true for first arrivals from elastic waves propagating through horizontally layered media, but is also recognized as a condition that might not occur in more complex geologies or when using other methods.

18. An extension of the argument for seismic crosshole testing was that other methods, such as electromagnetic (EM) (radar), acoustic, and resistivity methods, might also be used in the crosshole test mode. A number of government agencies, universities, and private firms were contacted to determine what hardware and techniques had been developed for crosshole testing. Positive responses were obtained from Southwest Research Institute (SwRI), Lawrence Livermore Laboratory (L^3), Tennessee Valley Authority (TVA), and Sonex, Ltd. A listing of the crosshole test capabilities of these organizations at the time (1979) is as follows:

Organization	Crosshole Test
TVA	Acoustic
SwRI	EM (radar)
L^3	EM (radar) resistivity
Sonex	Acoustic sonar

19. The TVA has made extensive use of single borehole and crosshole acoustic surveys for nuclear power plant-related site investigations in rock. The remaining organizations have conducted crosshole surveys for a variety of applications including tunnel detection studies sponsored by the U. S. Army Mobility Equipment Research and Development Command (MERADCOM). Since there was a capability in the area of interest of this study, arrangements were made for feasibility testing of these methods, as appropriate, at two WES research sites in Florida. Results of this testing are discussed in Part III.

PART III: FIELD EVALUATIONS OF SELECTED CROSSHOLE TECHNIQUES

20. As a part of its studies in the field of cavity and tunnel detection, the WES has made use of two karstic limestone test sites in Florida. The Medford Cave test site was originally selected to typify air-filled solution cavities in dry rock. The Manatee Springs test site was chosen to represent water-filled solution features in limestone below the water table. A site map showing the location of the test sites is presented in Figure 1. Plan views of the Medford Cave and Manatee Springs sites are shown in Figures 2 and 3, respectively. These figures also show the locations of borings and the outline of the main cavity system at each site. Figures 4 and 5 are profiles of the crosshole test areas showing the target features at the Medford Cave and Manatee Springs sites, respectively. More detailed documentation of the sites is available from reports now in preparation for publication (Cooper, in preparation; Butler, in preparation (a) and (b); and Curro, in preparation).

Crosshole Investigations at the Medford Cave Site

21. The Medford Cave site is located near Reddick, Fla., in Marion County. The site is characterized by a thin layer (typically from 0.9 to 1.8 m thick) of overburden underlain by Miocene Hawthorne formation limestone. Beneath the Hawthorne is the Eocene Ocala group (limestones). Extensive and complex air-filled solution cavities of up to 12 m width are found in the Crystal River formation of the Ocala Group at depths on the order of 3 to 9 m below the ground surface, although some features are known to be located as deep as 24 m below the surface.

22. A suite of conventional single borehole logging methods was selected for use at Medford Cave (a) to characterize the subsurface media for evaluation of crosshole test results, and (b) to address the question of radius of investigation using a known anomaly. Three

boreholes were drilled for these purposes and are identified as boreholes L-1, L-2, and L-3 in Figure 2. The borehole in closest proximity to the main cavity was borehole L-1, which at its closest approach was only about 1 ft (0.3 m) away from the main cavity. The suite of logging methods included borehole caliper, natural gamma, gamma-gamma density, and neutron devices. A summary of these results together with a profile showing the subsurface conditions near boring L-1 is presented in Figure 6. From Figure 6, it can be seen that neither the gamma-gamma measurement of bulk density nor the neutron measurement of moisture content in boring L-1 was influenced by the presence of a major cavity feature located only 1 ft (0.3 m) away from the borehole. Results from boring L-2 and L-3 were similar. However, the gamma-gamma bulk density and water content measurements are in reasonably good agreement with data obtained from core samples tested in the laboratory, results of which are summarized in Figure 7. Resistivity, acoustic televiewer, and sonic methods were not employed because these devices only operate in an open fluid-filled borehole, which could not be provided at the Medford Cave site. (All borehole fluid is immediately lost to the extensive cavities intersecting the boreholes.)

23. SwRI crosshole EM (radar) surveys were conducted at the Medford Cave site in 10 hole pairs with a transmitter in one hole and a receiver in the other (both at a common depth). A conceptual illustration of the SwRI crosshole EM system is shown in Figure 8. Only a few pertinent examples of the results obtained will be presented in this report. The first example is a control crosshole survey run between borings C4 and C5 (see Figure 2) on limestone strata believed to be free of cavities. Results of this crosshole test are shown in Figure 9, which is a plot of depth versus elapsed travel time for the EM pulse from transmitter (borehole C5) to receiver (borehole C4). In Figure 9, it can be seen that the pulse arrival signature is quite uniform and that the arrival time at the receiver in boring C4 is approximately 25 nsec for the depth interval from 13.1 to 46 ft (4 to 14 m). The next crosshole survey of interest was run between boreholes C2 (transmitter) and C5 (receiver), and this survey investigated the cavity features

shown in Figure 4. The shortest travel path between boreholes for this survey was about 35.1 ft (10.7 m).

24. Results of this survey are shown in Figure 10. Comparing Figures 9 (no cavities) and 10 (two cavities), it can be seen that the presence of the cavity features causes a pronounced change in character of the received EM signals plotted in Figure 10. Figure 11 is a plot of survey results from the same crosshole interval as shown in Figure 10 but with the EM transmitter in boring C5 and the receiver in boring C2. Figures 10 and 11 show that the results of the forward and reverse surveys using boreholes C2 and C5 are virtually identical, as might be expected. The results are thus very repeatable, and the presence of air-filled cavity features is indicated by:

- a. A decrease in travel time through the cavity zone (4 to 11.5 m in depth, Figures 10 and 11).
- b. Multipath reflections occurring at late times in the EM pulse wave train arriving at the receiver.

25. The phenomenon of decreased travel time through the cavity zone is explained by the difference in propagation velocity of the EM pulse in air and in the limestone at the site, i.e., $V_{air} \sim 2$ to $3 \times V_{limestone}$. EM (radar) pulse propagation velocity in the limestone may vary with material properties such as density, water content, presence of air- or soil-filled voids, etc. The EM (radar) pulse propagation velocity in air can be taken to be about 9.84×10^8 ft/sec (3×10^8 m/sec). Reflections occur from the walls, roof, and floor of the cavity, and are obvious in the wave train arriving at the receiver (Figures 10 and 11).

26. Another example of the detection of a cavity by crosshole EM methods is the survey between boreholes C2 and C3, results of which are shown in Figure 12. For the location of the cavity, refer to Figure 4 in which the cavity is seen to be in the depth interval from 29.5 to 37.7 ft (9 to 11.5 m). In Figure 12, the shortest travel time occurs at about the 26.2-ft (8-m) depth, and multipath reflections are seen in the depth interval from about 16.4 to 39.4 ft (5 to 12 m). The direct travel path from boring C2 to C3 was about 22 ft (6.7 m).

27. As an example of the distance over which EM signals can be propagated in dry limestone, consider the survey run between boreholes C4 (transmitter) and C6 (receiver), which are located about 88.6 ft (27 m) apart. Results of this survey are shown in Figure 13, and from Figure 2, it is seen that the direct travel path from boring C4 to C6 crosses the same cavity features indicated in Figure 4. Faint indications of the cavity are seen in Figure 13 as a reduced travel time at a depth of about 26.2 ft (8 m) in the first pulse arrival. This indication, together with reflection phenomena later in the wave train, is much more subtle than in previous examples but is still recognizable even for a direct travel path of 88.6 ft (27 m) between boreholes.

Crosshole Investigations at the Manatee Springs Test Site

28. The Manatee Springs test site is located near Chiefland, Fla., in Levy County, as shown in Figure 1. Overburden at the site is Pamlico terrace sand that grades to sandy clay with limestone nodules at the top of rock, which is typically encountered at depths of from 3.3 to 16.4 ft (1 to 5 m). Beneath the overburden is a sequence of limestones of which the top member is the Ocala formation, followed by the Williston, Inglis, and Avon Park formations.

29. The Ocala formation is a soft, massive white to pink coquina limestone comprised of fossiliferous remains set in a pasty calcite matrix. The Williston formation is a grey to brown limestone that is fossiliferous, granular in appearance, and varies from well to poorly cemented. The Inglis formation is a hard, silicified grey limestone which is vuggy. The Avon Park limestone is brown, vuggy, and weathered.

30. A plan view of the site showing boring locations and the outline of the main cavity features of interest are shown in Figure 3. A profile through the crosshole test area showing the boring locations and the target (cavity) features is presented in Figure 5.

31. As shown in Figures 3 and 5, the crosshole target at Manatee Springs is a secondary cavity or flow channel which connects to the main

underground stream feeding the surface spring. The target feature is irregular in cross section, has a maximum width of about 10 ft (3 m) in the depth interval from 91.6 to 107 ft (27.9 to 32.6 m) below the ground surface. Dimensions of the target cavity were measured by divers early in the drilling program, but the exact depth of the feature was not verified by drilling (boring E1) until all crosshole testing had been completed. The crosshole investigators were advised that divers' depth gages indicated the roof of the cavity to be at a depth of about 105 ft (32 m) but that some depth uncertainty could be expected since these gages had not been calibrated. An extensive lateral cavity network was encountered by all borings except C5 in the zone from 109 to 116 ft (33.2 to 35.3 m) in depth, as indicated in Figure 5. This cavernous zone is near the top of the Inglis formation and is just below the Williston-Inglis contact.

32. In order to provide a basis for judging results of the crosshole testing, a series of conventional single borehole logs were run in boreholes C2 and C3, which bracket the target cavity as shown in Figure 5. Results of the conventional logging using borehole caliper, neutron, gamma-gamma density, sonic, guard log resistivity, and borehole televiewer tools in borings C2 and C3 are summarized in Figure 14 for the depth interval of interest (40 to 120 ft (12.2 to 36.6 m)).

33. Referring to Figure 14, it can be seen that the lateral cavity features intersecting boreholes C2 and C3 in the depth interval from 105 to 115 ft (32 to 35.1 m) are readily detected by conventional logging methods, and are best delineated by the televiewer log. As expected, no indications are seen of the target cavity known to be located between borings C2 and C3 in the 91.6- to 107-ft (27.9- to 32.6-m) depth interval. In fact, from indications seen in the sonic and other conventional logs, one might reasonably conclude that this depth interval is characterized by relatively more competent rock than the strata above or below it. It is clear that a stratigraphic correlation based solely on these data would predict relatively competent rock in the 91.6- to 107-ft (27.9- to 32.6-m) depth interval. This would be entirely

incorrect, because it is known that the crosshole target cavity lies in this depth zone between borings C2 and C3.

EM (radar) testing

34. A detailed description of the SwRI radar study at Manatee Springs is available from the literature (Herzig and Suhler, 1980), so only a summary of results will be presented in this report.

35. To provide a control for comparison of the crosshole test data, the SwRI EM (radar) tools were first used to survey between boreholes C2 and C5, 17.5 ft (5.3 m) apart, because no significant cavity features are known to exist in this section.

36. For convenience in comparisons to be developed later, the C5/C2 crosshole test results, and other EM and acoustic crosshole data are summarized in Figure 15. In Figure 15, it can be seen that the C5/C2 radar (EM) pulse travel times are reasonably consistent from 40 to 115 ft (12.2 to 35.1 m) in depth. The subsurface media in this depth interval between borings C5 and C2 is believed to be essentially free of cavity features and may be regarded as competent rock for this test site. Average pulse travel time from boring C5 to boring C2 in the 60- to 115-ft (18.3- to 35.1-m) interval was typically on the order of 60 to 80 nsec.

37. Also shown in Figure 15 is the SwRI radar results from a crosshole survey from boring C2 (transmitter) to boring C3 (receiver). These boreholes bracket the crosshole target cavity whose top is at 91.6 ft (27.9 m) in depth, as shown in Figure 15. Comparing the two radar (EM) plots C5/C2 and C2/C3 in Figure 15, it is seen that:

a. Radar pulse travel times from boring C2 to C3 were about two times greater than from boring C5 to C2, as expected.

b. In Figure 15 (for C2/C3) there is a marked change in EM pulse amplitude and frequency at a depth of 90.2 ft (27.5 m). Note that the top of the target cavity is at 91.6 ft (27.9 m).

c. No radar pulse arrivals could be detected below 100 ft (30.5 m) in depth; i.e., signal attenuation in the media was severe below this depth.

38. According to information furnished by SwRI, the presence of water-filled cavities would tend to both increase the travel time through

such zones and also to severely attenuate signal pulses, as is apparently the case in this instance.

Acoustic tests

39. Three acoustic crosshole studies were made at the Manatee Springs test site and results from two of these have been reported (TVA, 1980; Sigma Industrial Systems, 1981). The third study was conducted by Sonex, Ltd., a company organized by staff of Sigma Industrial Systems after its dissolution, and was carried out using ex-Sigma personnel and equipment. This final study was performed in September 1981, and preliminary results are presented later in this report.

40. Since detailed results of the first two acoustic studies are available from the literature, only pertinent details will be discussed in this report. The first acoustic (sonic) study was performed by the TVA and results of their single borehole conventional acoustic survey are summarized in Figure 14. Unfortunately, little crosshole data were obtained, and none in the zone of interest, because the high-energy TVA crosshole sparker source malfunctioned. This signal source basically consists of a bank of capacitors which, upon command, deliver a high-voltage charge to two electrodes encased in a borehole sonde. By this means a brief but very intense spark, or electrical discharge, is induced across a preset gap between the electrodes. Shock waves from the event are transmitted through the metal jacket of the sonde to the borehole fluid, and then to the subsurface media. This is a reasonably common method of generating relatively high-energy (approximately 100 joules) seismic signals for use in the crosshole mode; however, the TVA sparker unit could not deliver its rated energy level on this occasion. Three lesser energy pulsed crystal sources, operating in the 40 kHz, 27 kHz, and 17 kHz range, were successfully used in the conventional single borehole logging mode but could not provide detectable signals in crosshole tests with spacings greater than about 20 ft (6.1 m) between source and detector. Hence, no crosshole comparisons are possible and the limited TVA crosshole data are not presented herein.

41. A second acoustic crosshole study was performed by Sigma Industrial Systems in July 1980. This work, sponsored in part by

MERADCOM, was done before the actual depth of the target cavity had been established. Unfortunately, this initial work was encouraging but did not adequately cover the depth interval of interest and so is not presented. However, the MERADCOM consented to provide funding for another attempt which was carried out by personnel of Sonex, Ltd. in October 1981. Initial results of this investigation are summarized in Figure 15. The left-hand acoustic plot in Figure 15 is the result of a common depth survey with the receiver located in boring C5 and the transmitter rock with little or no cavity development, and the acoustic results tend to support this conclusion because the pulse travel time through the media is approximately 1.5 to 2 msec throughout the 80- to 120-ft (24.4- to 36.6-m) depth interval. This equates to an average compression wave velocity of about 10,000 ft/sec (3049 m/sec) in the material based on the shortest travel path of 17.5 ft (5.3 m) between boreholes.

42. Next, a common depth acoustic crosshole survey was made from boring C2 (source) to boring C3 (detector). Results of this survey are shown in the right-hand acoustic plot in Figure 15. Comparing acoustic plots C5/C2 and C2/C3 in Figure 15, the following observations can be made:

a. When no significant cavities are present and the rock is relatively competent (survey C5/C2), the received crosshole signals are reasonably uniform in terms of arrival time, frequency, and amplitude.

b. Where solution cavities of significant size are known to exist as in the 90- to 120-ft (27.4- to 36.6-m) depth interval in survey C2/C3, and crosshole acoustic signals are severely attenuated, there is a pronounced change in frequency of the received signals, and there is a pronounced increase in signal travel time through the media.

c. At the depth of the lateral cavity network in survey C2/C3 (approximately 105 to 115 ft (32 to 35.1 m)), the crosshole acoustic signals are so severely attenuated as to barely be detectable.

d. At the depth of the target cavity (91.6 to 107 ft (27.9 to 32.6 m)) in survey C2/C3, there is a very distinctive diffraction pattern in the secondary wave train

arrivals at the detector in boring C3. This phenomenon is attributed to the presence of the target cavity because no similar pattern is found elsewhere in the C5/C2 or C2/C3 surveys, and the diffraction pattern is what one would expect under the circumstances.

43. In the case of the C2/C3 survey, results at the depth of the target cavity (in the zone where the distinctive diffraction pattern was noted) are of considerable interest. It is possible to compute direct pulse travel time through the media in order to validate the observed response. If it is assumed that the travel time through competent rock is about 3.0 msec, from the C3/C2 acoustic survey record in Figure 15 at about 85 ft (25.9 m) depth, then a representative rock velocity (P-wave) can be derived from

$$V = \frac{D}{T} = \frac{30 \text{ ft}}{3.0 \text{ sec}} = 10{,}000 \text{ ft/sec } (3049 \text{ m/sec}) \qquad (1)$$

where

D = distance from boring C3 to boring C2, ft or m

T = pulse travel time, boring C3 to boring C2, sec

44. It is known that the spacing between boreholes is 30 ft (9.15 m), the cavity is about 10 ft (3 m) wide at its maximum point, and the cavity is filled with water whose velocity is about 4800 ft/sec. If it is assumed that the acoustic pulse travels in an essentially horizontal path between boreholes, then it can be said that

$$\text{Total travel time} = T = t_r + t_w \qquad (2)$$

where

t_r = pulse travel time in rock, sec

t_w = pulse travel time in water, sec

or

$$T = \frac{20 \text{ ft}}{10{,}000 \text{ ft/sec}} + \frac{10 \text{ ft}}{4800 \text{ ft/sec}} \qquad (3)$$

$$T = 0.0020 + 0.0021 = 0.0041 \text{ or } 4.1 \text{ msec}$$

45. Referring again to the C3/C2 acoustic record shown in Figure 15, it can be seen that the actual travel time through the target cavity zone at 100 ft (30.5 m) in depth is about 4.0 msec, which is considered to be in reasonably good agreement with the known conditions.

46. In subsequent crosshole acoustic tests, the source and detector were offset in depth by arbitrary increments and the C2/C3 survey was repeated. This procedure allows the investigator to better define the target of interest by viewing it at different angles. The sequence of offset surveys produced the results shown in Figure 16 (Sonex, Ltd., 1982). The signature of the target cavity was taken to be the diffraction pattern first noticed in the second arrivals from the C2/C3 common depth acoustic survey, results of which are shown in Figure 15. Ray travel paths from transmitter (C2) to receiver (C5) were used to indicate the top and bottom of the cavity in Figure 16. As can be seen in Figure 16, the known depth and vertical dimension of the target cavity are well defined by the offset survey results (crosshatched zone).

Resistivity test

47. Crosshole resistivity measurements were also carried out by L^3 at the Manatee Springs site. This method typically requires fluid-filled boreholes and so could not be applied at the Medford (dry boreholes) site. The equipment configuration for the survey is shown in Figure 17. To induce an electric field, the downhole current electrode was energized with commutated DC current. (The other current electrode was located on the surface at some distance from the borehole.) A voltmeter was connected between the downhole and surface potential electrodes so as to measure the electric potentials induced in the subsurface media.

48. Measurements were conducted by holding the downhole current electrode in a fixed position, while the downhole potential electrode was moved up or down in the adjacent borehole. Results of this crosshole survey between borings C2 and C3 are shown in Figure 18. Measurements were made for every 1-ft (0.3-m) increment of the downhole potential electrode for the depth interval of 89 to 138 ft (27.4 to 39 m). As shown in Figure 18, the data identify a significant resistivity anomaly

in the 114- to 120-ft (34.7- to 36.6-m) depth interval. Referring to Figure 15, it can be seen that this resistivity anomaly must be the extensive lateral cavity feature that intersects boreholes C2 and C3. No indication of the crosshole target cavity feature is seen in Figure 18, indicating that this crosshole resistivity method probably cannot detect features other than those which intersect the borehole. This being the case, conventional logging tools provide the same capability and have the advantage of simplicity and superior resolution for features intersecting the borehole.

49. While this crosshole resistivity method apparent does not have the desired detection capability, it is possible that better results could be obtained by using alternative electrode configurations. Research to this end is being now carried out at the WES, and results of electrical analog modeling studies indicate that the crosshole resistivity "guard" electrode configuration shown in Figure 19 should offer significant advantages in sensitivity and resolution. However, the WES-proposed system has not yet been validated in the field.

PART IV: SUMMARY OF DOWNHOLE GEOPHYSICAL CAPABILITIES

Single Borehole Methods

50. Conventional single borehole logging methods are capable of providing a continuous record of material properties for subsurface strata which intersect the borehole. As discussed in this report and in the literature (Headquarters, Department of the Army, 1979), conventional logging data may be used for qualitative interpretations of stratigraphy and lithology, and may also be used, under favorable conditions, for quantitative analyses to determine significant engineering properties such as bulk density, porosity, etc.

51. The principal limitation of conventional single borehole methods is that the tools used have a radius of investigation which is typically only approximately 1 ft (0.3 m), as illustrated in this study. Consequently, the presence of anomalies located near but not intersecting the borehole cannot be detected by conventional single borehole logging methods. In order to investigate rock media at distances of more than 1 to 2 ft (0.3 to 0.6 m) from the borehole, given the current state of the art, it is necessary to employ crosshole techniques such as those discussed in the next section.

Crosshole Methods

52. In this study, crosshole acoustic and EM (radar) crosshole methods were successfully used to identify known zones of poor-quality rock, i.e., cavernous areas, situated between boreholes spaced up to 90 ft (27.4 m) apart in dry rock. The ability to detect zones of poor-quality rock which are not penetrated by a borehole represents a significant advance in the state of the art.

53. It is also clear from results obtained in this study that there is a need for higher intensity energy sources for investigations in rock below the water table. At Manatee Springs, for example, all of the investigators were unsuccessful in propagating signals of

measurable amplitude from boring C2 to boring C3, a distance of 30 ft (9.15 m), at the level of the extensive and complex horizontally developed cavity network which was encountered in borings C2 to C4. A reasonable conjecture is that the EM and acoustic signal travel path through this cavity labyrinth is tortuous, and as a consequence transmitted signals are drastically attenuated by a sort of natural "muffler" effect. However, severe signal attenuation is in itself a prime indicator of poor-quality rock.

54. As noted earlier in this study, the Manatee Springs test site can certainly be termed a severe test for any downhole geophysical method. Some general observations about the effect of geologic conditions on downhole geophysical investigations are presented next.

Effect of Geologic Conditions on Downhole Investigations

55. There are several important limitations which geologic conditions impose on downhole investigations. For example, at this writing, there are no proven techniques for effectively coupling high-frequency acoustic (sonic) energy sources to the media in dry open boreholes. The presence of fractures or cavernous zones in dry rock frequently causes loss of circulation, so that little or no drilling fluid remains in the borehole after drilling. In order to retain fluid in the hole, it may be necessary to grout and redrill or to case the hole and grout. In extreme cases, such as when numerous large fractures or cavities are encountered in rock, neither grouting nor casing will serve to retain fluid or to provide good energy coupling of the signal source to the rock strata. In this case, it will be difficult if not impossible to use acoustic (sonic) tools above the water table.

56. Fortunately, EM (radar) tools can be effective in dry rock, as at the Medford Cave site, and are well adapted to use in the cross-hole test mode. Electromagnetic (radar) devices operate in the megahertz frequency range, and these very high-frequency signals tend to attenuate rapidly when water content in the strata is increased.

Complete saturation and complex geologic conditions, as at the Manatee Springs (wet) site, may restrict radar penetration to less than 30 ft (9.1 m) in the crosshole mode. For saturated strata and fluid-filled boreholes, the acoustic (sonic) tools are the first choice of method to use in single borehole and crosshole modes since they operate in the kilohertz or lower frequency range, generally suffer less signal attenuation as a consequence, and are designed to be used in fluid-filled boreholes.

57. As has been stressed previously, geologic conditions at the Manatee Springs test site posed a very severe (but completely realistic) test of downhole geophysical methods. Aside from the complex conditions at this site, the P-wave velocity contrast ratio between limestone and voids (water-filled) was relatively low, being about $\frac{\text{10,000 ft/sec (limestone)}}{\text{5,000 ft/sec (water)}}$ or 2. For cavernous or fractured zones in more competent saturated rock media, the P-wave velocity contrast ratio could be appreciably higher; for example, water-filled fractures or void zones in other dense competent rock could provide a velocity contrast ratio of, say, $\frac{\text{18,000 ft/sec (rock)}}{\text{5,000 ft/sec (water)}}$ or 3.6. For the case of competent dry rock, the velocity contrast ratio could be $\frac{\text{18,000 ft/sec (rock)}}{\text{1,100 ft/sec (air voids)}}$ or about 16.4. The argument is that detection capability is enhanced by favorable geologic conditions such as high velocity contrast ratios, i.e., $\frac{\text{rock velocity}}{\text{void velocity}}$, and that crosshole results obtained at the Manatee Springs test site probably represent a worst case example of detection capability in saturated rock. It is believed that even better crosshole results can be expected in most instances, particularly if higher energy signal sources are employed or if refined recording techniques, such as signal stacking, are developed.

Recent Developments in the State of the Art

58. The ideal device to detect and delineate zones of poor-quality rock would require only a single borehole, either dry or

fluid-filled, and would have the capability to sense direction, distance, dimensions, and physical properties of target features at ranges on the order of tens of metres. There is currently no single device with such capabilities; however, recent technology has produced either field-tested techniques and equipment or research which should be noted for possible future application to U. S. Army Corps of Engineers projects.

59. A method receiving continued attention in the field of geophysics has been the use of borehole microgravimeters to sense mass anomalies in rock at considerable depths. To date, this technology has been successfully applied to prospecting for hydrocarbons (Snyder, 1976), ore bodies, and evaluation of rock density changes due to underground nuclear blasts.

60. The borehole microgravimeter can survey through casing and its lateral radius of investigation is relatively large in comparison with the vertical spacing of measurement stations. A typical example of vertical stationing versus radius of investigation (zone of influence) is shown in Figure 20. From Figure 20 it is seen that the lateral radius of investigation can be taken to be five times the vertical spacing between measurement stations. Of course, the field of influence is omnidirectional in a plane normal to the borehole axis, so the direction of discrete anomalies located at some distance from the borehole is not sensed by a single survey. It should be noted that a much greater volume of the surrounding media is sensed by the borehole gravimeter than by conventional single borehole logging instruments. Unfortunately, time and funding constraints precluded field testing of this type of equipment in this study.

61. Research is also being directed to developing a directional downhole EM (radar) system. The concept is to develop a directional antenna so that images of remote targets can be obtained from a single borehole. This technology will be very useful, if developed, but presents a formidable challenge in terms of the antenna design and signal intensities required to investigate targets at any appreciable range in attenuative media (notably the coquina limestones encountered at the Manatee Springs test site).

62. Finally, the WES and other investigators are studying the problem of coupling acoustic signal sources to dry borehole walls, a problem which to date has restricted the use of such devices to fluid-filled holes. Also, several types of pulse-echo sonar systems are in use, but these systems generally would benefit from the development of higher intensity signal sources. The future may well bring such sources, as well as significant improvement in the speed and accuracy of data analysis.

PART V: CONCLUSIONS AND RECOMMENDATIONS

63. The presence of poor-quality rock or voids in the foundation for major structures can be a problem of critical proportions. Even if an extensive drilling program is conducted, there is always the possibility that a feature of significant size and potentially hazardous nature might be missed. It is all too frequently the case that the needed remedial measures are also very expensive.

64. In this study it was determined that crosshole acoustic and EM (radar) surveys can detect such features provided that the borings are spaced no more than 30 to 50 ft (9.1 to 15.2 m) apart, depending on site conditions. Combining selected conventional single borehole logging methods with the crosshole surveys provides a means to detect zones of poor-quality rock with good confidence, as exemplified by the detection in this study of a 10-ft-wide solution cavity in limestone below the water table. In any case, it is necessary to carefully assess geologic conditions in order to select the appropriate geophysical method and achieve reasonable results.

65. Where geologic conditions are both simple and well documented, as for example, massive unfaulted horizontal stratigraphy, then site characterization can usually be established with minimum effort and a reasonable degree of confidence. However, a much greater degree of uncertainty typically exists for complex geologies, when site conditions have not been well documented, or the structure is of a critical nature. In these instances, geophysical methods can provide a cost-effective program to improve confidence in site characterization.

66. Based on results of this study, the following tabulation is offered as a general guide in selecting an appropriate suite of geophysical methods to detect zones of poor-quality rock or voids between boreholes:

Geophysical Methods	Suggested Spacing Between Boreholes* (Crosshole)	Measurement Parameter	Indication of Poor-Quality Rock or Voids
		Dry Rock	
Caliper**		Borehole diameter	Increase in borehole diameter
Gamma-gamma density**		Bulk density	Decrease in bulk density
Natural gamma**		Stratigraphy	--
Crosshole radar (EM)	50 ft (15.2 m)	EM pulse travel history	Decrease in travel time, altered wave train
		Wet Rock	
Caliper**		Borehole diameter	Increase in borehole diameter
Gamma-gamma density**		Bulk density	Decrease in bulk density
Natural gamma**		Stratigraphy	--
Uphole sonic**		P-wave travel time history	Increased travel time, altered wave train
Crosshole sonic	30 ft (9.1 m)	P-wave travel time history	Increased travel time, altered wave train
Crosshole radar (EM)	20 ft (6.1 m)	EM pulse travel time history	Increased travel time, altered wave train

* Based on results obtained in this study.
** Conventional single borehole logging method.

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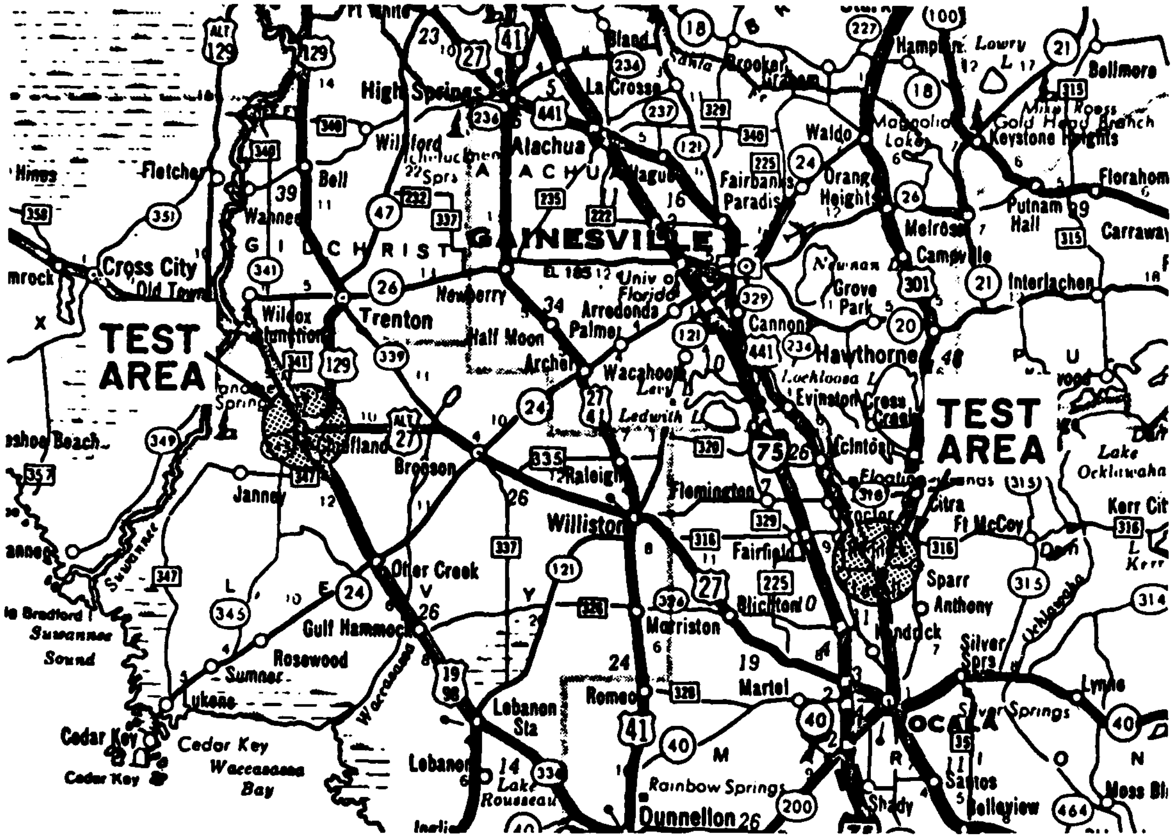

Figure 1. Location of Manatee Springs and Medford Cave (Reddick, Fla.) test sites

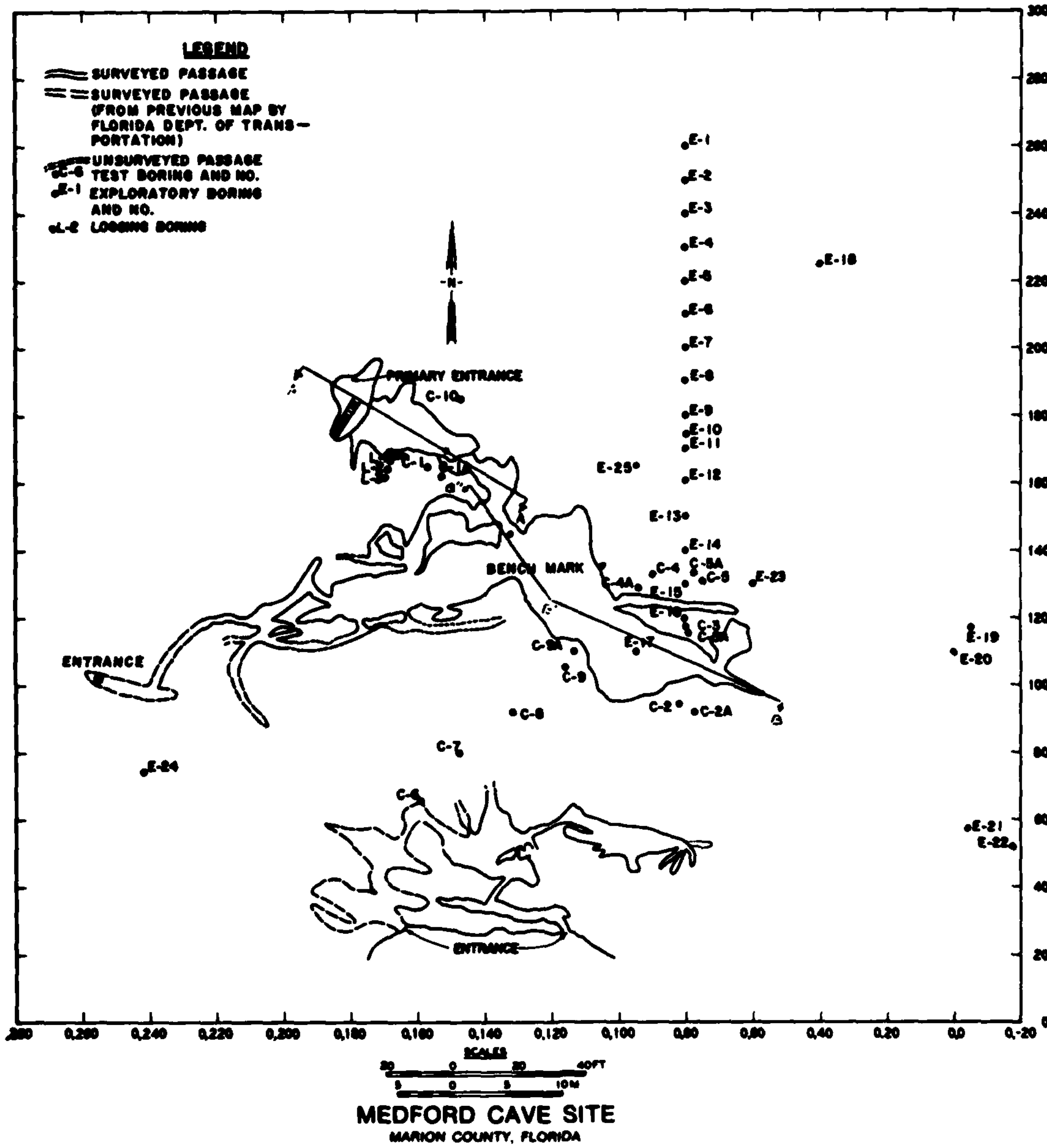

Figure 2. Plan view of the Medford Cave test site showing the cavity system and boring locations

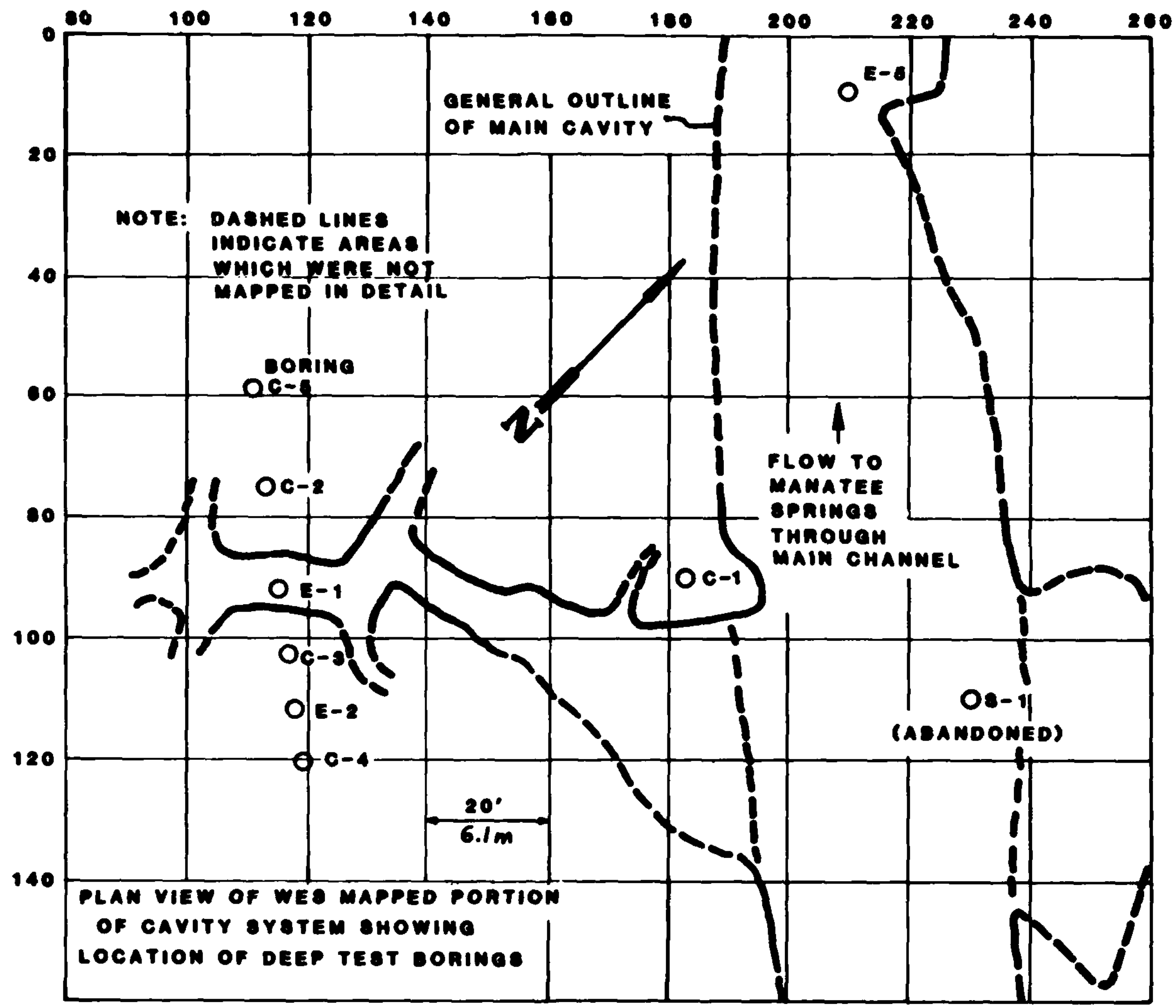

Figure 3. Plan view of the Manatee Springs test site showing the cavity system and boring locations

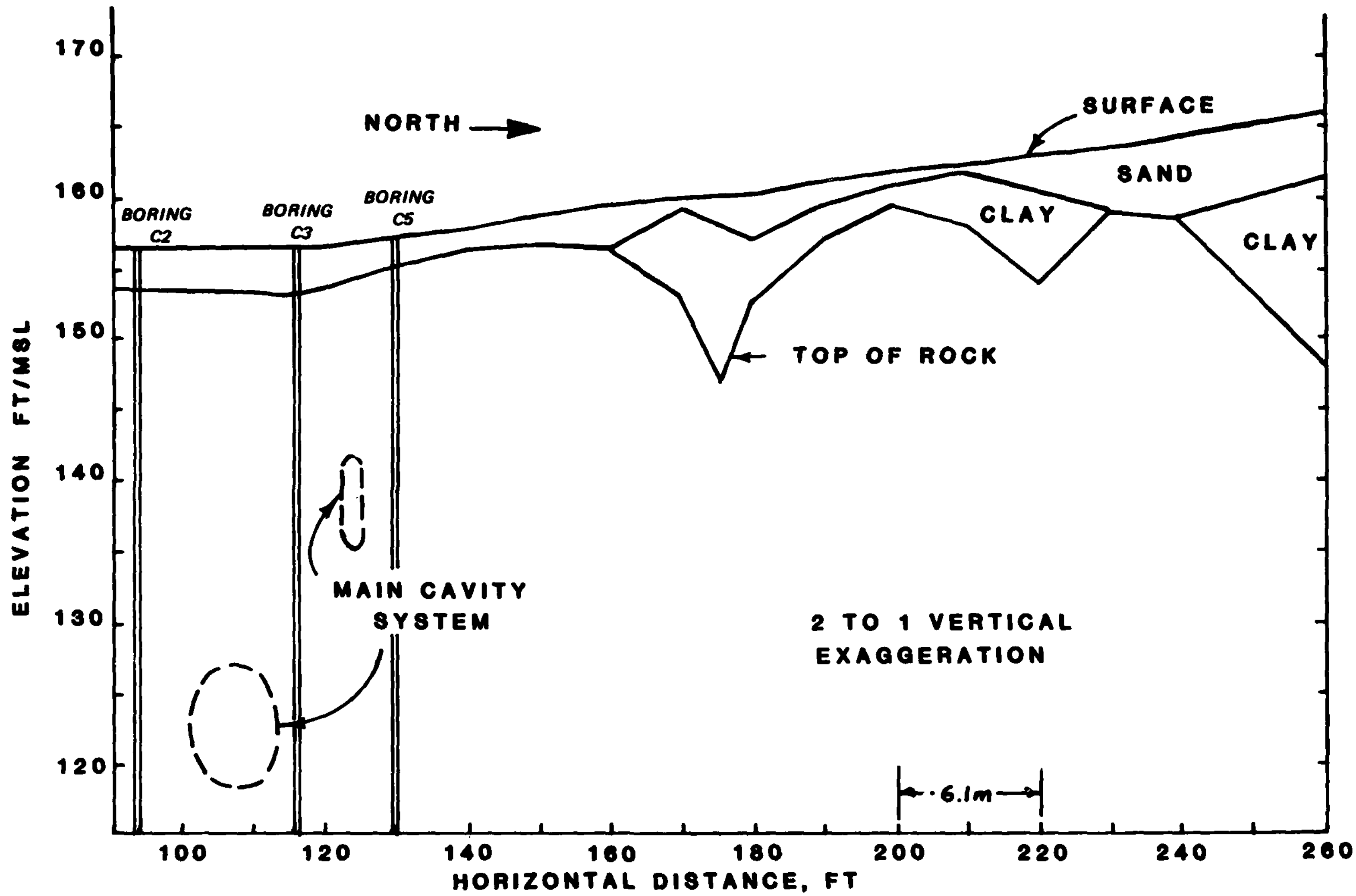

Figure 4. Subsurface profile of the Medford Cave crosshole target area

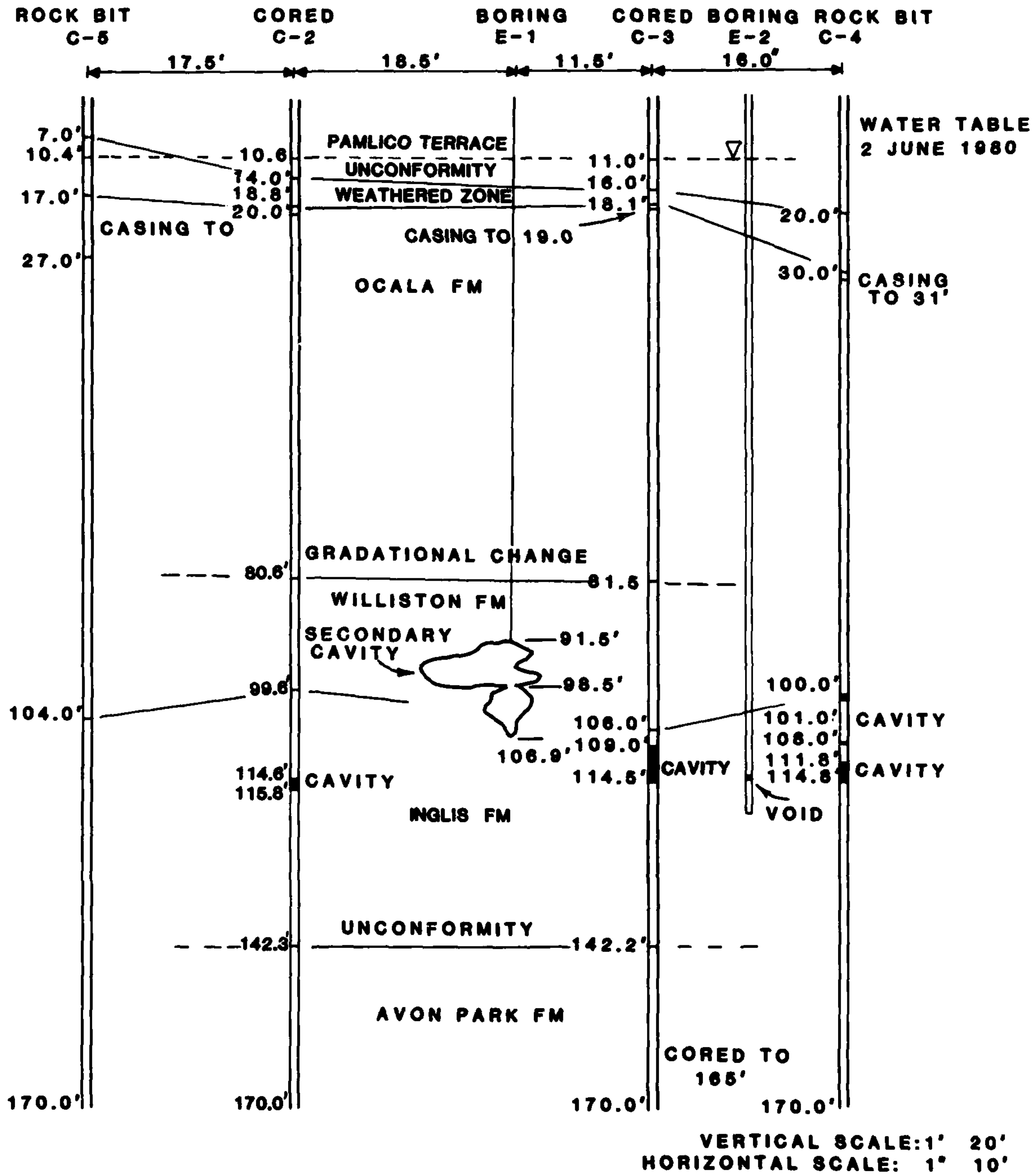

Figure 5. Subsurface profile of the Manatee Springs crosshole target area (To convert feet to metres, multiply by 0.3048.)

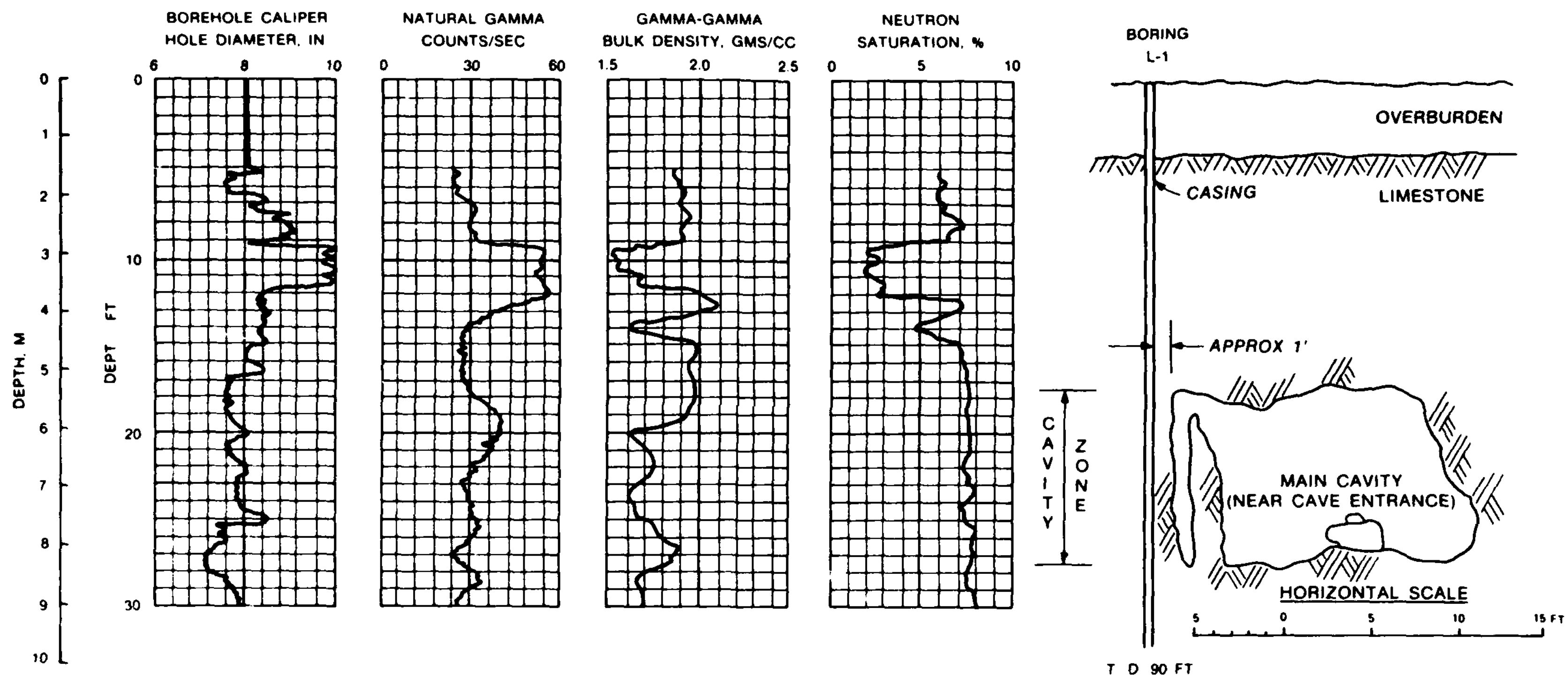

Figure 6. Summary of conventional single borehole logging results at the Medford Cave site

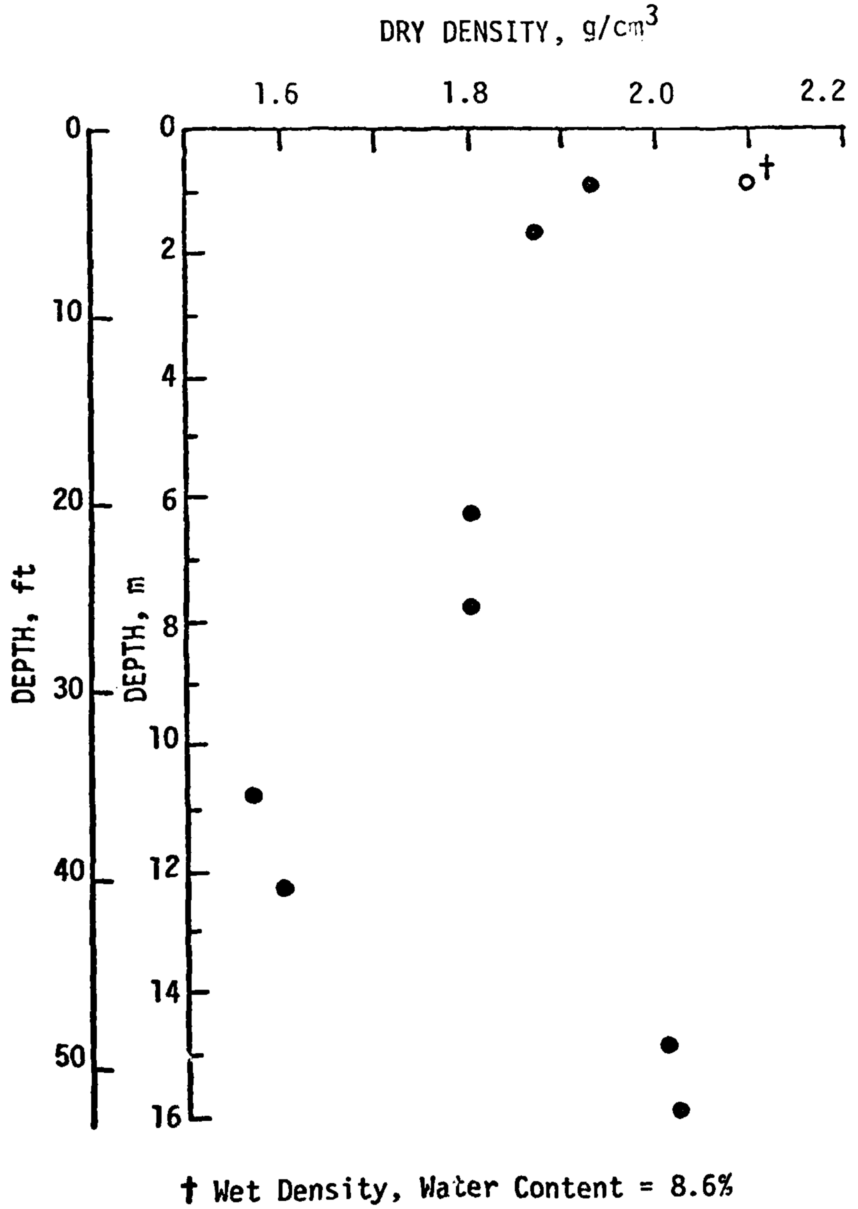

Figure 7. Laboratory determinations of dry density and water content from core samples obtained in boring C6

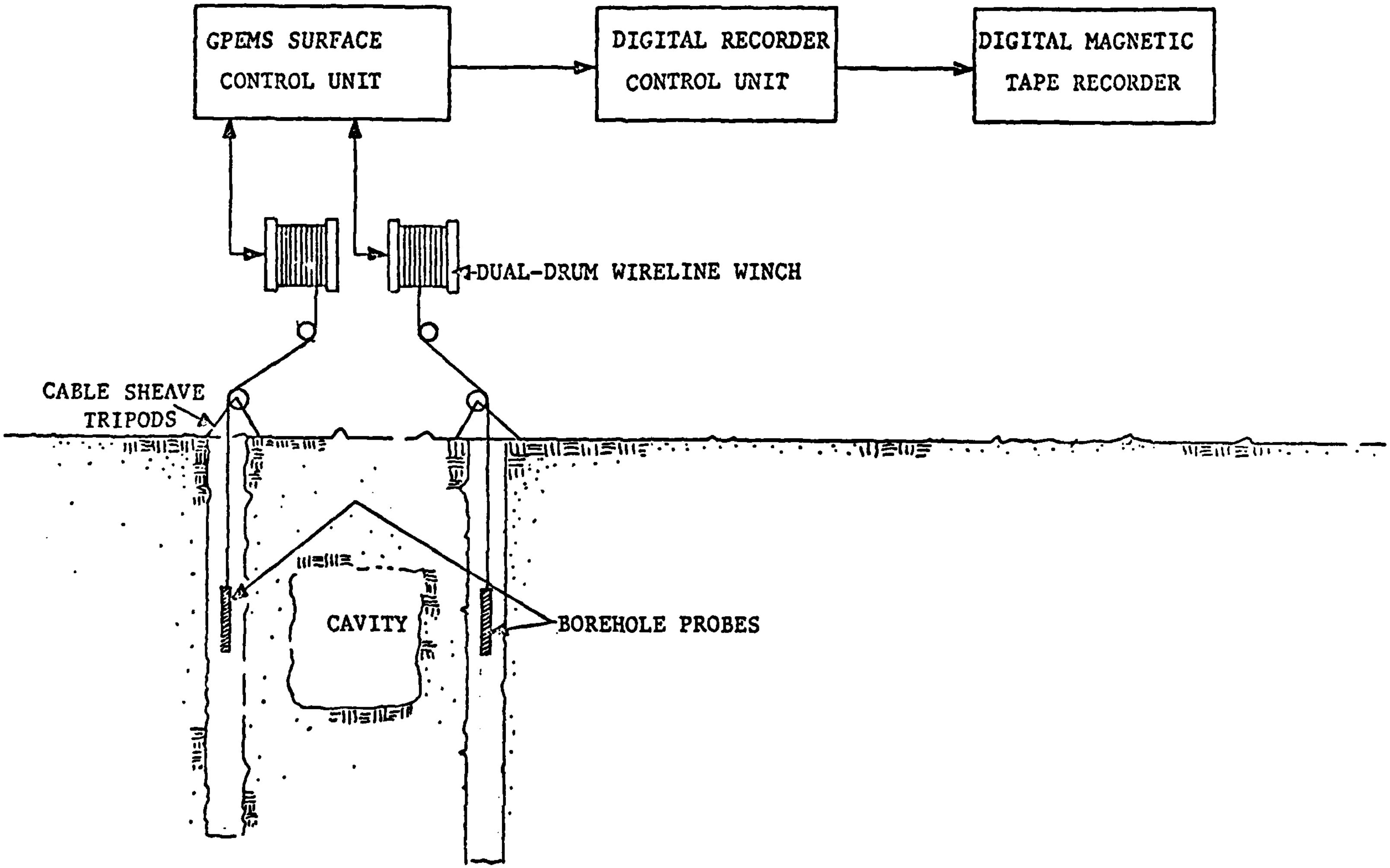

Figure 8. Conceptual illustration of the ground-penetrating EM system

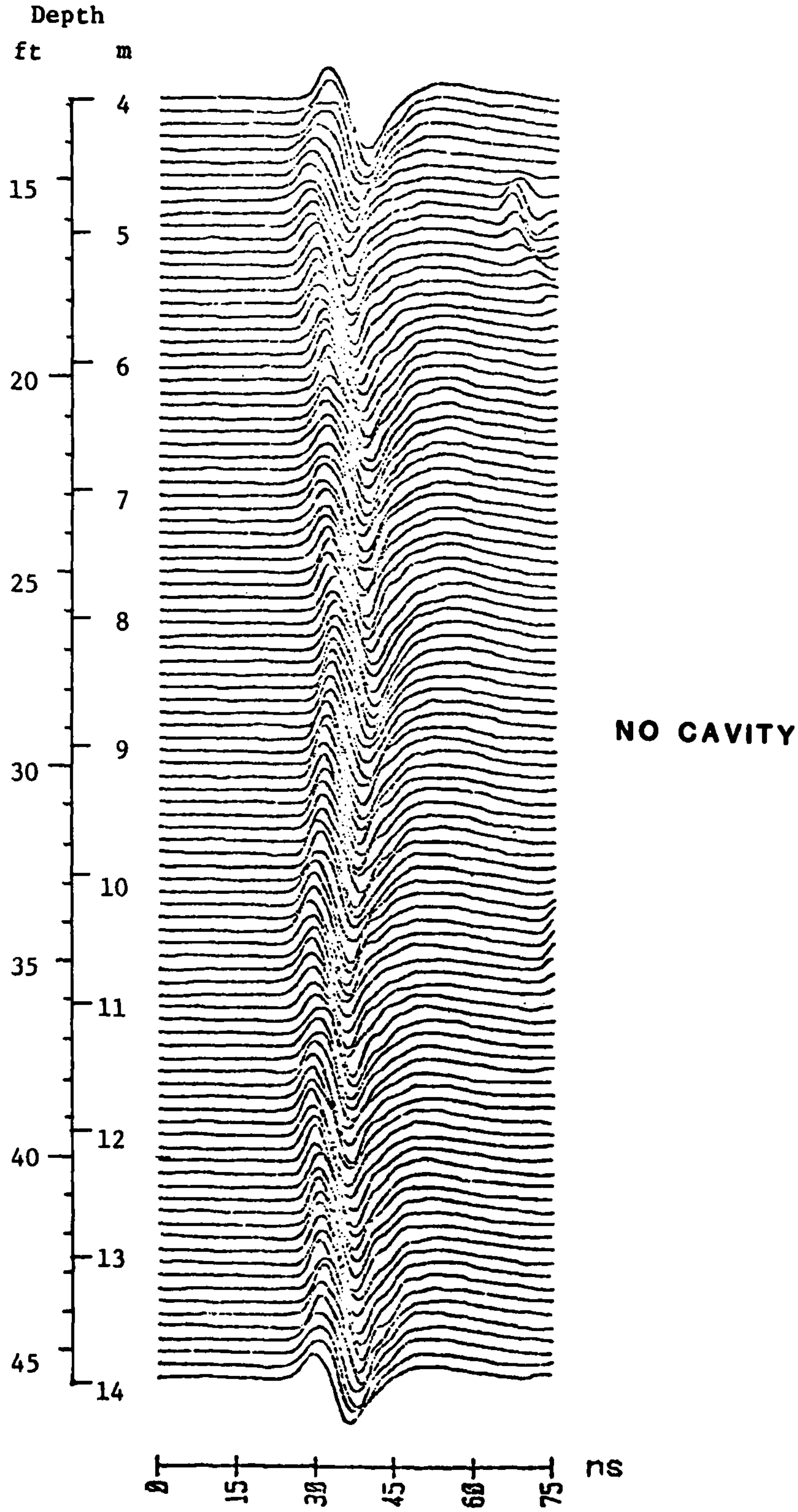

Figure 9. Crosshole EM (radar) survey results from Medford boring C5 (source) to boring C4 (detector), 4.3 m apart

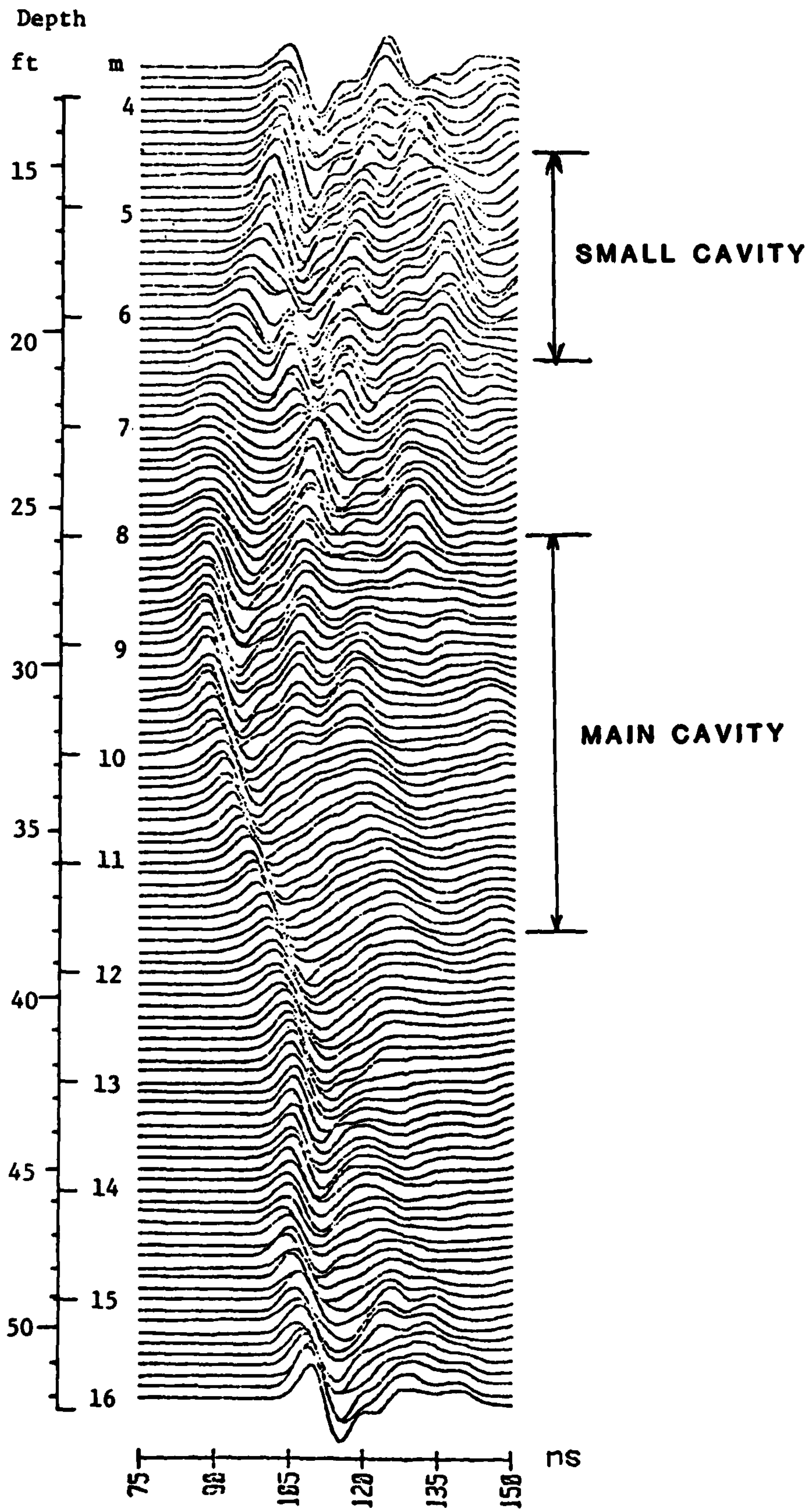

Figure 10. Crosshole EM (radar) survey results from Medford boring C2 (source) to boring C5 (detector), 10.7 m apart

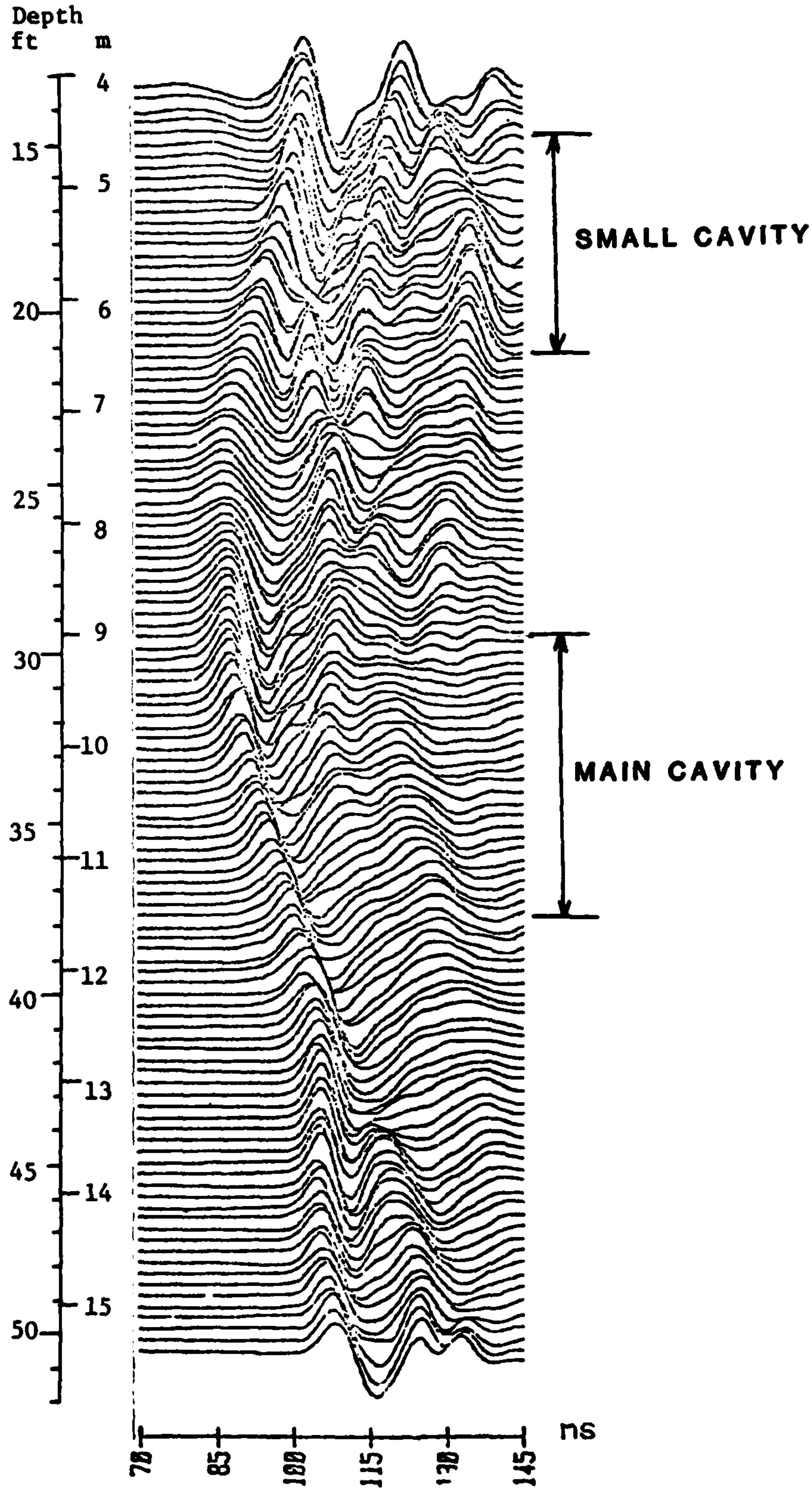

Figure 11. Crosshole EM (radar) survey results from Medford C2 (source) to boring C5 (detector), 10.7 m apart

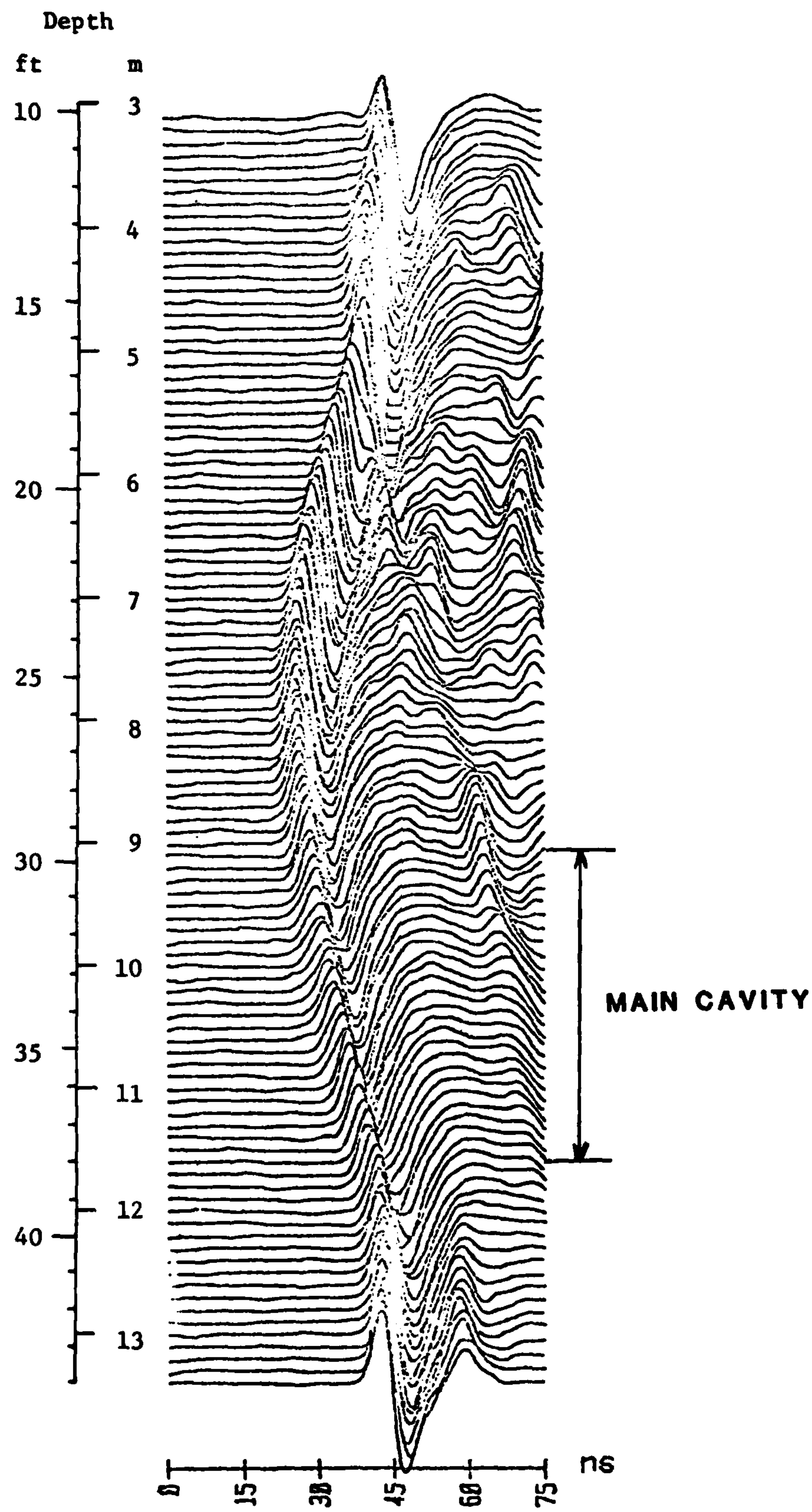

Figure 12. Crosshole EM (radar) survey results from Medford boring C2 (source) to boring C3 (detector), 6.7 m apart

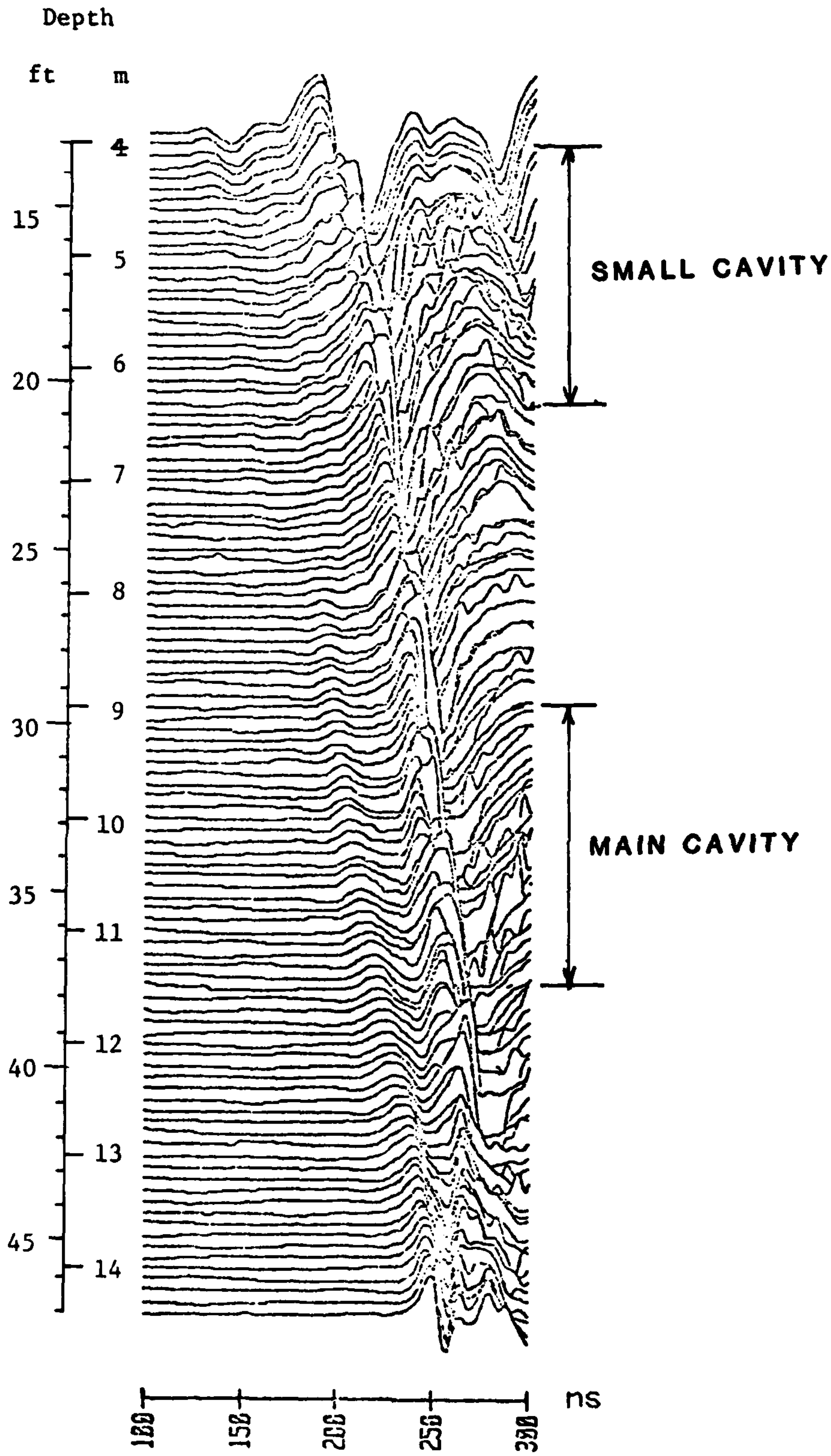

Figure 13. Crosshole (radar) survey results from Medford boring C4 (source) to boring C6 (detector), 27 m apart

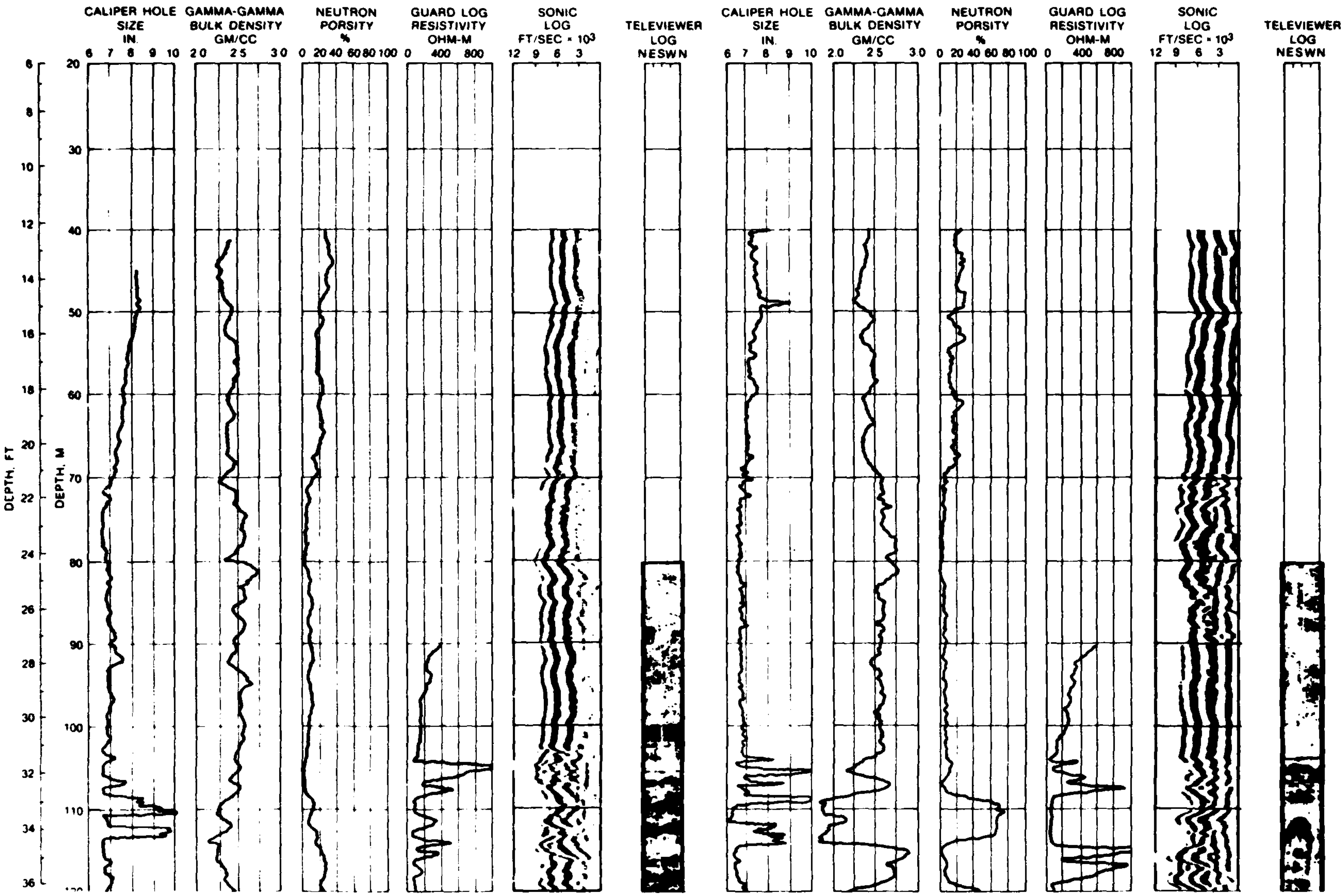

Figure 14. Summary of conventional single borehole logging results at the Manatee Springs site

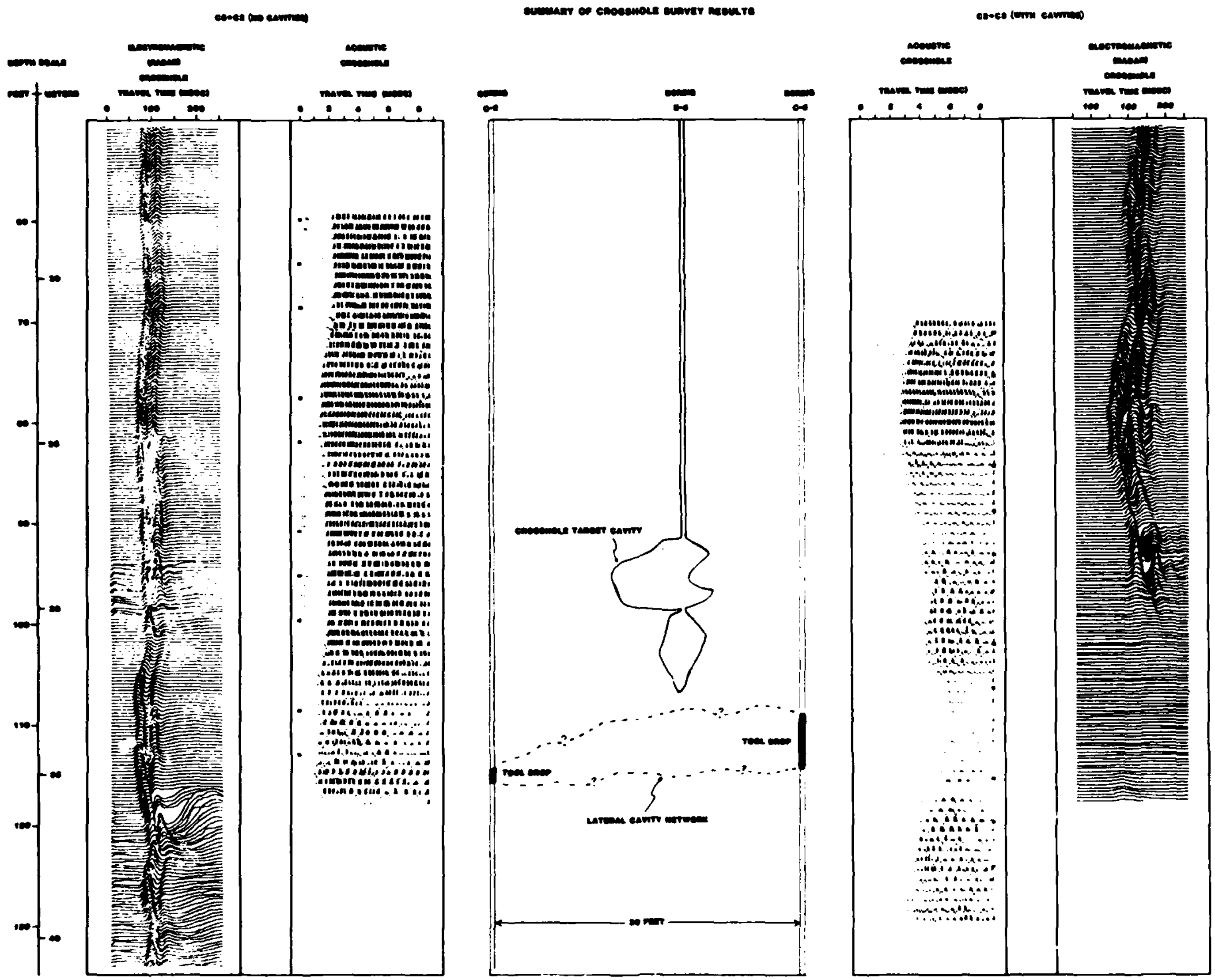

Figure 15. Summary of crosshole test results at the Manatee Springs site

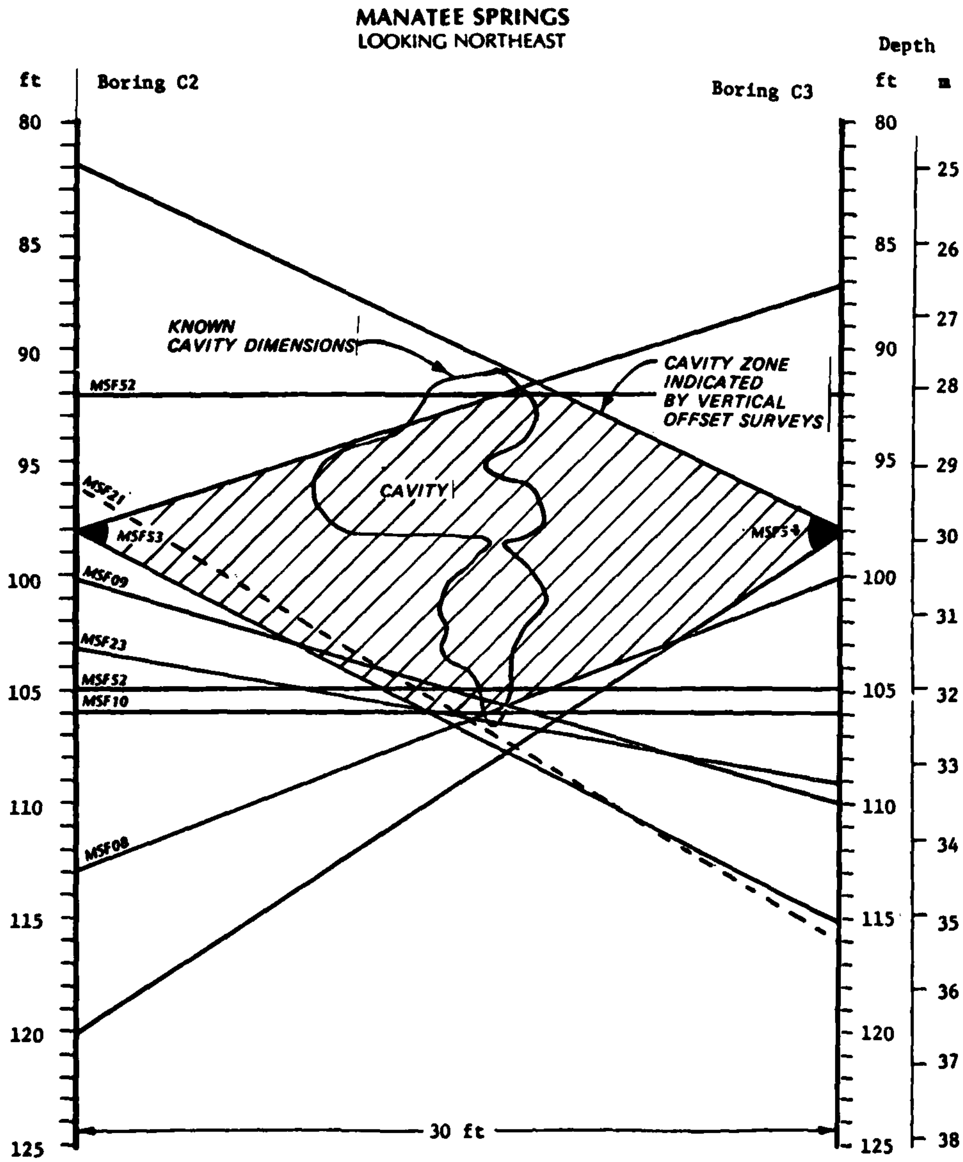

Figure 16. Cavity location by vertical offset crosshole acoustic tests

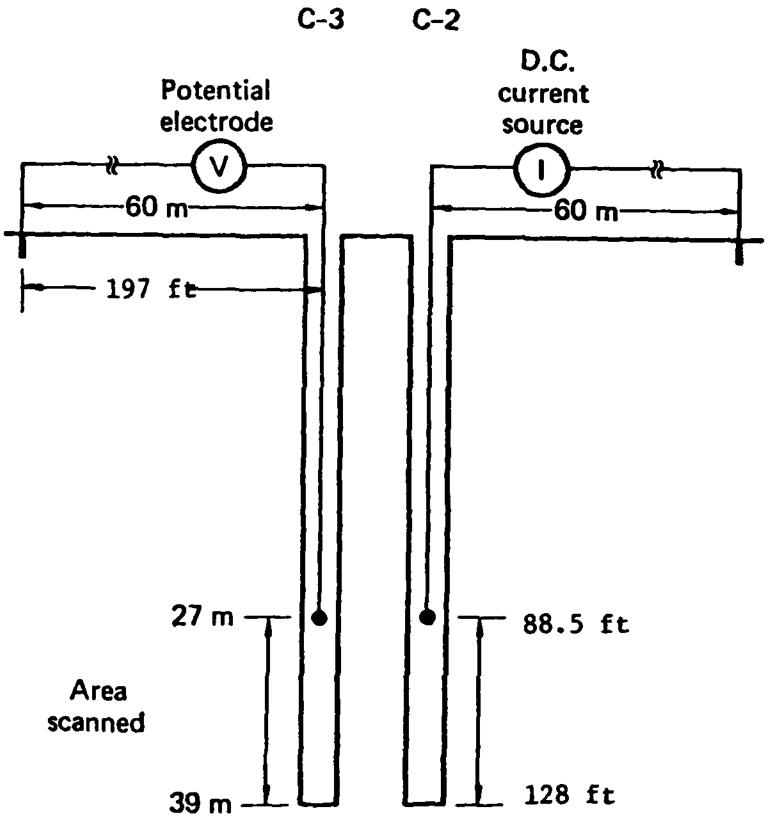

Figure 17. Block diagram of L^3 crosshole resistivity equipment

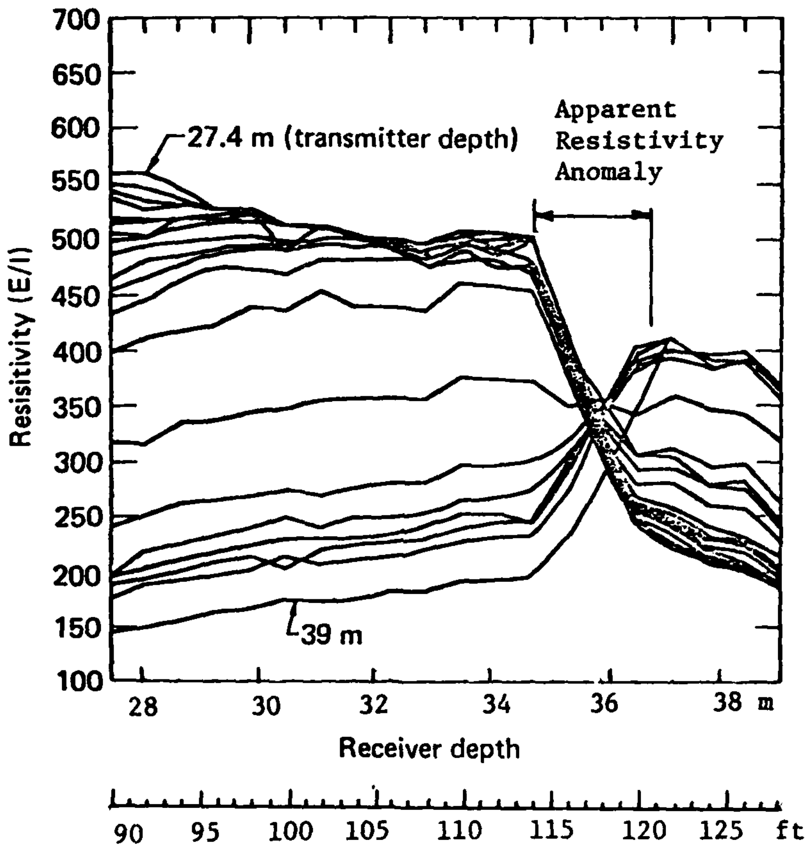

Figure 18. Results of L^3 crosshole resistivity survey between boreholes C2 and C3, Manatee Springs test site

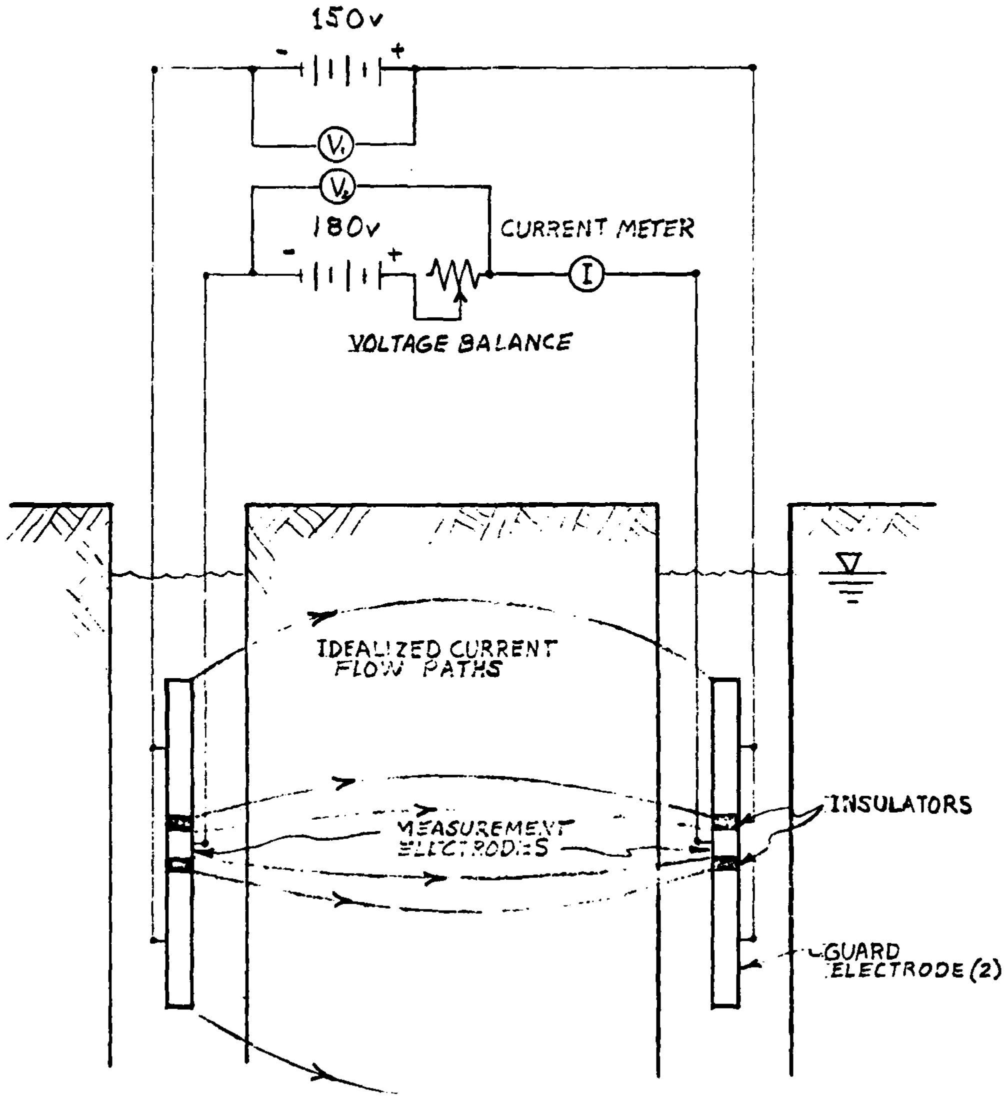

Figure 19. Schematic of proposed WES crosshole resistivity apparatus

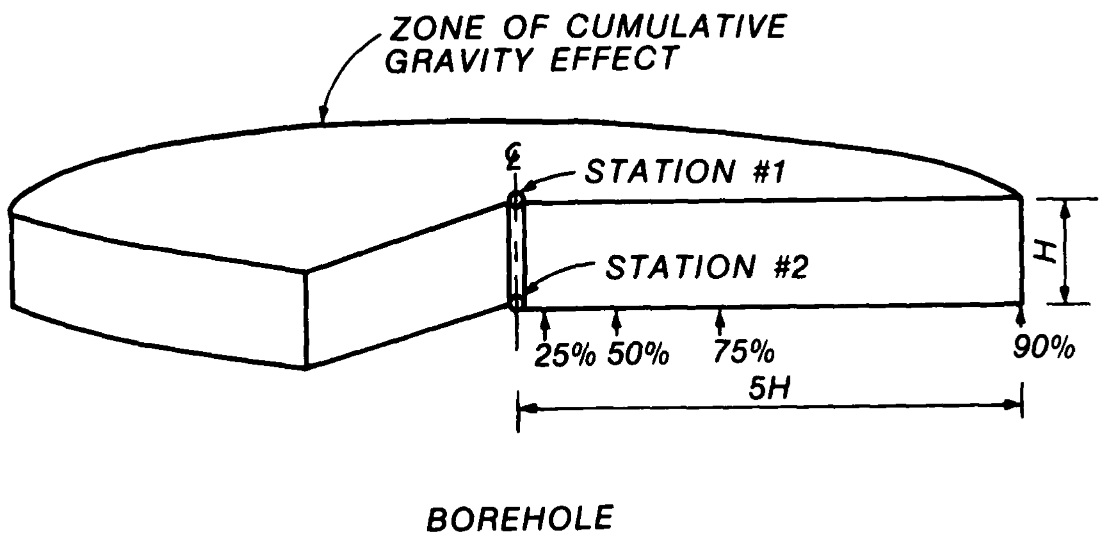

Figure 20. Theoretical zone of influence for single borehole microgravimeter survey

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Cooper, Stafford S.
The use of downhole geophysical methods to detect zones of poor-quality rock or voids / by Stafford S. Cooper (Geotechnical Laboratory, U.S. Army Engineer Waterways Experiment Station). -- Vicksburg, Miss. : The Station ; Springfield, Va. ; available from NTIS, 1982.
30, [20] p. : ill. ; 27 cm. -- (Miscellaneous paper ; GL-82-15)
Cover title.
"September 1982."
Final report.
"Prepared for Office, Chief of Engineers, U.S. Army under Project 4A161102AT22, Task AO, Work Unit 003 and CWIS Work Unit 31150."
Bibliography: p. 29-30.

1. Boring. 2. Geophysical instruments. 3. Geophysical research. 4. Rocks--Acoustic properties. 5. Rocks--Testing. I. United States. Army. Corps of Engineers.

Cooper, Stafford S.
The use of downhole geophysical methods to : ... 1982.
(Card 2)

Office of the Chief of Engineers. II. U.S. Army Engineer Waterways Experiment Station. Geotechnical Laboratory. III. Title IV. Series: Miscellaneous paper (U.S. Army Engineer Waterways Experiment Station) ; GL-82-15.
TA7.W34m no.GL-82-15

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